US Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources

GUIDELINES FOR RISK AND UNCERTAINTY ANALYSIS IN WATER RESOURCES PLANNING

Volume II

- Examples-

March 1992 **IWR REPORT 92-R-2**

Guidelines for Risk and Uncertainty Analysis in Water Resources Planning

Volume II

- Examples -

Prepared for
U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources
Fort Belvoir, VA 22060-5586

Prepared by
The Greeley-Polhemus Group, Inc.
105 South High Street
West Chester, PA 19382

March 1992

IWR Report 92-R-2

GUIDELINES AND PROCEDURES FOR RISK AND UNCERTAINTY ANALYSIS
IN CORPS' CIVIL WORKS PLANNING

Volume II: EXAMPLE CASES

TABLE OF CONTENTS

Part I: FLOOD CONTROL PAGE

TABLE OF CONTENTS (Continued) PAGE

Part II: NAVIGATION

TABLE OF CONTENTS (Continued)

LIST OF TABLES PAGE

Part I: FLOOD CONTROL

TABLE OF CONTENTS (Continued)

LIST OF TABLES PAGE

Part II: NAVIGATION

TABLE OF CONTENTS (Continued)

LIST OF FIGURES PAGE

Part I: FLOOD CONTROL

Part II: NAVIGATION

LIST OF FIGURES PAGE

Part I

FLOOD CONTROL

FLOOD CONTROL

INTRODUCTION

The Heck Valley Flood Control Case Study is a hypothetical study prepared to illustrate and support the principles and selected techniques described in the Guidelines and Procedures for Risk and Uncertainty Analysis in Corps' Civil Works Planning and accompanying Appendices. It uses real data from Corps' projects wherever possible in order to represent realistic situations. The data and issues presented in the case study do not represent or depict any past, present or future Corps' project or study.

Because the case study is hypothetical and uses data that were collected without risk and uncertainty analysis in mind, it has been necessary to fabricate certain data. When this has been done, an effort was made to keep the fabricated data and situations consistent with the overall case study.

The case study begins with an overview of the hypothetical study. It proceeds by addressing specific planning/analytical issues raised in the study. These issues, though fairly wide-ranging, represent a mere sample of the analyses and decisions that lend themselves to risk and uncertainty analysis. The sections of the case study are written to more-or-less stand on their own. This format accommodates selective reading and avoids the unnecessary expenditure of energy on making all of the details of the case study fit together as smoothly as they would in an actual study.

To keep the analysis tractable and the text reasonably reader-friendly, the detailed examples of the risk and uncertainty techniques employed in this case study are provided for one community only. Thus, while the discussion of initial formulation issues begins with a regional focus, this focus gives way to a single community focus. The analysis of several communities in a single plan would generally require a simple duplication of the types of analyses and judgments presented for the hypothetical community of Tonsking.

The case study itself is organized in six major sections roughly corresponding to the steps of the planning process. As the planning process is dynamic and continuous, the decision to discuss and illustrate certain issues and concepts in one section rather than another is often arbitrary. This neither diminishes the analysis nor hampers the planners in doing real analysis and reporting the results.

OVERVIEW

The study area is located along the Heck River in northeastern Midstate, in a region of Maiden County known as Heck Valley. There is a long history of flooding in the Heck Valley, documented as far back as the early 18th century. Following devastating floods in the 1930's, a Federal project, known as the Heck Valley Project, was constructed.

The existing flood control system was completed in 1943. It consists of about 13 miles of earthen levee and steel capped sheetpile wall protecting the communities of Tonsking, Catonsville and Irvington, on the right bank, and Westchester and Marydell, on the left bank, of the Heck River. Protection is continuous on the left bank. The right bank communities are each protected by individual systems. The entire system was designed to protect against a flood magnitude of the March 1936 flood, being 232,000 cubic feet per second (cfs), and estimated at that time to be a 50-year flow.

Eight reservoirs have been built on tributaries of the Heck River upstream from the Heck Valley area since 1943. Six other reservoirs have been authorized but have not been built, due to either a lack of economic feasibility, or local opposition.

In the late 1970's, dredging advocates succeeded in getting a Congressionally-authorized special study of the channel dredging alternative for Heck Valley. In 1982, Tropical Storm Hilda, the flood of record, caused in excess of $2 billion damage in the Heck Valley. Following the 1982 flood, an accelerated post-flood study of the area indicated that it would be feasible to raise the existing protection.

The initial formulation of this hypothetical study considered the reservoir, dredging and levee-raising alternatives. The levee-raising alternatives were found to be the most feasible. The formulation issue shifted to the selection of the optimal level of protection.

Only the dredging alternatives presented significant environmental issues. The presence of an existing project has circumscribed potential adverse impacts of the levee-raising alternatives.

The Heck Valley is located in coal country, and coal mining was the industry around which these communities were built. In the 1960's, coal mining was phased out as the mines were economically depleted and demand for the high sulfur coal in the Valley vanished. Massive unemployment resulted in a 20-year decline in population that appears to have stabilized. The garment industry has replaced coal as the major industry of the area. Efforts to diversify the community's economy have succeeded in stabilizing the economy of the Valley. At present, the community is stable. Declines of the recent past have halted. Future growth prospects are bright, but that growth will take place in new communities in the county. The floodplain is effectively fully-developed. The few acres of available land were acquired and cleared as a result of the 1982 flood.

There are two issues of special significance in the study. First, land subsidence is a severe problem. It is a result of natural foundation conditions and the Valley's underlying honeycomb of mine shafts. The existing levee system has experienced stability problems as a result of the subsidence. A comprehensive levee stabilization program is underway and is expected to be completed long before the base year for a new project. The engineering division maintains that though subsidence will continue, the existing system is stable. Future subsidence could have a significant effect on project costs for any levee-raising project as well as presenting an analytical problem for modeling the performance of levee freeboard.

The second issue is induced flooding. There are six communities up or downstream from the project area that could have their flood problem exacerbated by a levee-raising project. BERH review of the post-flood feasibility report flagged induced flooding as a significant issue. Neither time nor money was allocated for detailed economic, engineering, or environmental studies of these areas.

SPECIFICATION OF PROBLEMS AND OPPORTUNITIES

Problem identification is a critical step in the planning process. It is also a frequently overlooked step. The flooding problem has long been recognized in the Heck Valley. Prior to the Hilda flood of 1982, the potential for floods in excess of the existing level of protection was recognized. This was the basis for the authorization of the river dredging study.

Looking beneath the surface, however, it would appear that the real problem in the 1960's and 70's was the decline of the economy for reasons entirely unrelated to flooding. The flood threat was a handy scapegoat for Valley officials who were having difficulty coming to grips with the fact that the world and Heck Valley's economy were changing fast and forever. A significant minority of the river dredging proponents saw the dredging operation as the means to a cheap source of timber (from the islands to be removed) and of coal (that was believed to line the river bottom). They were motivated more by short-term economic gains than by long-term flood protection.

Tropical Storm Hilda came at a time when the economy had begun its rebound, and it succeeded in galvanizing a fairly well focussed consensus on the nature of the problem in Heck Valley. Flooding was clearly a problem. The non-Federal partner, or "official public," wanted higher levees because the problem was obvious to them--water comes over the top of the levee.

An early and effective public involvement program succeeded in identifying the public's views of the problem. The "unofficial" public in the protected communities was helpful in pointing out interior drainage problems that had escaped the attention of local authorities. The "unofficial" public in nearby unprotected communities effectively, if not eloquently, made it clear that induced flooding was a very real concern, if not a real problem.

By going beyond the definition of the problem offered by the "official" public, specifically, by seeking out the general public in the protected communities and those that are unprotected, the interior drainage and induced damage problems could be incorporated effectively in the planning process. This served two purposes. First, it allowed for a more rational planning process. Second, it provided ample time for the agency to deal with the policy issues that arose concerning induced damages.

The methods employed to help eliminate uncertainty concerning the nature of the problem in the Heck Valley included a questionnaire, workshops, and focus groups. The questionnaire, issued at a series of public workshops and reprinted as a paid advertisement in the county newspaper, asked

Date	Stage	Damages
July 24, 1982	40.9	$2-3 billion
April 1, 1904 (1)	35-37	$0.45 million
May 2, 1934 (2)	33.1	$0.2-0.3 billion

(1) No gage at this time, stage was approximated from reported high water marks on Market Street bridge and related to the existing gage at that location.
(2) This is a translation of the gage reading from the old River Street gage to the Market Street gauge.

Table 1: Heck Valley Flood History - Highest Known Floods

the simple question, "What is the problem that the Corps of Engineers should be addressing?"

The workshops, small and informal, were held in eight different locations. Each workshop included a session called, "What's the Problem?" In these sessions, individuals were provided the opportunity to tell analysts what they viewed as the problem. The focus groups included the Chamber of Commerce, the Heck River Basin Association (the dredging proponents), and other community groups. The groups restricted their discussion to an identification of the problem to be addressed by the Corps, and the problems that could not be reasonably addressed by the Corps. Flooding in the Heck Valley remained the primary concern of the study.

The Flood Problem

Every Corps' study that describes a flood problem addresses the historical flood record and the severity of the problem. The historical record will often include an estimate of the flow, frequency, and damages of a historical flood. These values must be put into a proper perspective by the analyst. Flows may have been estimated before there was a gage, or with a gage that has since been replaced. Are the reported frequencies based on the current frequency curve? Improved or natural conditions, etc.? What is the source of the damage estimate? A newspaper article, a windshield damage estimation, a detailed damage survey, etc.?

An example of putting this information into perspective is demonstrated in Table 1, and the following text.

> Stage data for floods prior to the installation of the River Street gage in 1921 are considered very unreliable. There are no good estimates of damages for the past floods. Detailed stage-damage surveys had not been conducted for the area prior to the current study effort. Hilda damages were based on an educated guess by Corps' personnel during the post flood activities. The 1902 event damages are from a newspaper account of the flood. The 1932 damages were estimated

based on unsupported file data from the 1943 construction project.

Once again, the changes are subtle and, perhaps, ultimately insignificant. The new direction indicated by this approach, however, is very significant. Incorporating risk and uncertainty analysis at its most basic level means telling the decision-maker what we know and when we knew it.

Stage, frequency, and damage information are dimensions of the flood problem fraught with uncertainty that will be addressed in considerable detail in subsequent sections. For the moment, we recommend the analyst present the data in a way that clearly indicates the fact that our analysis is imprecise. For example, the following paragraph discusses the existing project:

> The existing flood control system, completed in 1943, was designed to protect against a flood the magnitude of the May 1934 flood, estimated at the time to have been a flow of 232,000 cubic feet per second (cfs). This is currently estimated to have a recurrence interval between 33 and 125 years, with the best estimate being a 55-year flood. Current hydraulic and hydrologic analyses best estimates show that freeboard of the existing protection would most likely contain a maximum flow of about 290,000 cfs., estimated to range from about a 45- to 200-year event, with a best estimate being a 75-year event. Based on a 75-year level of protection, statistically there is a 76 percent chance that the existing level of protection would be exceeded one or more times in a 100-year period. Using a 200-year level of protection results in about 2-in-5 chances (40 percent) of one or more floods over a 100-year period. In either case, this is considered an unacceptably high risk. The protection was last exceeded in 1982.

Average annual existing flood damages in the study area are estimated to range from $0.5 to 16.9 million, with an expected value of $5.5 million.

Planning Objectives

Planning objectives are used initially in guiding the formulation of alternative plans and subsequently in their evaluation. The following planning objectives were developed and used in the formulation process for the 1990-2090 period of analysis. Those planning objectives that directly address the concerns of a risk and uncertainty analysis are marked with an asterisk.

1. Reduce flood damages in those communities currently protected by the Federal flood control system.*
2. Preserve and enhance recreation and open space land use opportunities.
3. Preserve and enhance community cohesion.
4. Reduce potential for loss of life.*
5. Maintain and enhance the integrity of the local economy.
6. Maintain or increase the quality and/or quality of fish and wildlife habitat.
7. Maintain or improve water quality.
8. Reduce health hazards due to flooding.*
9. Minimize the need for the relocation of homes and businesses.
10. Harmonize with existing land use plans.

11. Minimize adverse effects on cultural resources.
12. Maximize aesthetic quality in those areas of the community adjacent to project.
13. Avoid or minimize transfer of existing or creation of new risks, specifically, minimize induced flood damages and flooding in communities upstream and downstream of the study area.*
14. Minimize anxieties and concerns over flood threats.*
15. Minimize disruptions to the flow of automobile and rail traffic.
16. Achieve acceptable level of residual risk.*
17. Make maximum use of available information and data.*
18. Minimize model, parameter, and other types of uncertainty.*

Some of these objectives are typical of many flood control studies. It is important to note that good planning objectives cannot be identified and agreed upon unless the uncertainty surrounding the problems and opportunities faced by the study area is lessened early in the planning process. Careful problem identification is essential to the development of good objectives.

Several of the objectives relate explicitly to matters of risk and uncertainty. The first objective is an excellent example of risk analysis that has been accomplished by the Corps for decades. Later in this case study, we will consider ways to improve upon that analysis. The fourth and eighth objectives are also classical risk questions. The determination of when we have an acceptable risk to life--100-year protection? SPF protection?--is a risk management issue.

Objective 13 indicates that the best plan will minimize the creation of new risks for other parties. In the case of Heck Valley, that means a good plan will minimize or mitigate induced damages. Interior drainage analysis presents another opportunity for risk transfer. Depending on the interior drainage structures chosen, it is possible that some homes could be exposed to a new risk from ponding. The important point is that new risks come in all sizes and may be found in the least likely places. Generally, the best plans will be those that avoid or minimize both the transfer of risks from one area to another, and the creation of new risks.

Objective 14 hinges on effective risk communication and educating the public about the problems/risks that they face without and with the project. Closely related to Objective 14 is Objective 16. It is possible to look on the determination of an acceptable level of risk and the determination of the level of protection as essentially the same issue. However, to the extent that projects create new risks, the notion of risk and acceptability in this objective must be expanded. For example, in Heck Valley it is not sufficient to determine an acceptable level of risk by deciding the level of protection in the protected communities. An acceptable level of risk must be determined for those people living in the ponding areas and the communities affected by induced flooding.

Objectives 17 and 18 address not only the performance of the plan, but the evaluation process used to develop it. It requires the analysts to explicitly trade-off their own state of belief about the certainty of project costs, benefits, performance, impacts, etc.

INVENTORY AND FORECAST

Existing Conditions

Problem identification is the first critical step in the planning process. Typically, problem identification includes a description of existing conditions. This description frequently consists of a long litany of the various types of resources present in the study area.

Emphasis in this section should be placed on honestly reporting the tentativeness of our knowledge about the resources in the study area. Rather than presenting precise numbers, that in truth lack certainty, ranges of values should be used. It is not always possible to explicitly state the level of confidence we have in our data. The range of values the author presents can serve the same purpose subjectively by the mere fact of the interval width, i.e., a narrow range will generally indicate a greater degree of confidence than a wide range, provided the ranges are established objectively. These ranges can be chosen by the analyst to represent her/his degree of belief in the actual data.

Frequently, the data used to describe the study area may be of different vintage and quality. This can be frankly acknowledged in the study document as follows:

> In this study, 1980 Census data are used along with data obtained from feasibility study analyses as recently as 1988 and file data on the reservoir projects from the 1960's. The origins of some secondary sources of data, e.g., local planning documents, are not known. In every case, the data presented are believed to be the best data available.

While the content of this simple paragraph is wholly unremarkable, it does represent a significant step forward in risk and uncertainty analysis. It is a first step out of the denial phase and the beginning of an acknowledgement that we do not know everything. The hope is that those who find the quality of the data used unacceptable will be willing to pay for improvements to the data base.

Acknowledgment of the tentativeness of our knowledge should be carried forward throughout the study process. Not all of this needs to be presented in the report. The vast majority of data and analysis and, consequently, the risk and uncertainty assessment and management will be found in project files. The simple act of communicating the reality of a lack of certainty can be conveyed as shown in Table 2.

The table depicts drainage areas relevant to the project. The ranges in values may be accounted for by the quality (or lack of quality) of the available topographic mapping, measurement errors (whether planimetered, digitized, or otherwise estimated), or for any number of other reasons. The analyst can feel much more comfortable saying the Heck River drainage area below Moses Creek is between 9,900 and 10,000 square miles than she/he can saying it is 9,921 square miles. The range is small as a percentage, indicating that the analysts confidence level is reasonably high. The best estimate is the one that will be used when it is necessary or convenient to present a single numerical value.

The estimate of the Moses Creek drainage area has a much smaller absolute range (1.5 square

Stream	Approximate Drainage Area at Mouth (sq. miles)	
	Range	Best Estimates
Moses Creek	18.5-20.0	19.5
Old Mill Creek	39.0-42.0	40.0
Tyler Creek	36.0-38.0	37.4
King David Creek	18.0-19.5	19.0
Heck River:		
Below Moses Creek	9,900-10,000	9,921
Below King David	9,965-10,085	10,026

Table 2: Drainage Areas - Heck River and Tributaries in the Heck Valley

miles compared to 100 square miles), but the relative range is much larger. This indicates less confidence in this particular estimate. Once again a best estimate is available. The range is not a balanced one. The range indicates the best estimate could be high by 1 square mile or low by 0.5 square mile. This reflects a "conservative" best estimate.

None of the ranges have confidence intervals attached to them. They are the subjectively determined representation of the analysts' beliefs about the numbers. Statistical analysis is preferred when it is available. In the absence of empirical support, professional judgment can be displayed as shown in the table.

For the most part, such displays of information will require little or no additional work. In some cases, knowledge may be precise. For example, a physical description of the existing Federal project involves no uncertainty. It can be measured and described precisely. Foundation information may be equally precise, or it could be quite uncertain depending on the drilling program and other factors. In other cases, information may appear to be precise while in fact it is not. A good example of this is land use data. Land use data are obsolete almost as soon as they are collected because the land market is so dynamic.

Rather than continue to use very precise estimates of land use categories that we know are changing, a range of possible values is used. For example, the secondary data source (County Planning Commission Document) says open space comprised 15,451 acres. The overall significance of these data are minimal, so a reasonable estimate was made based on the published data as subjectively adjusted by our judgment of the changes that have taken place since the data were published. It is perhaps more reasonable to present the information in a report as follows:

> At the time of this study, it was estimated that 60-65 percent of the land was open space. Most of this land is not developable, however, due to the mountainous terrain and strip-mined areas. Of the developed areas, 9-11 percent was commercial, 14-15 percent was in semi-public uses, 6-7 percent was used for transportation. In 1989, the Heck Valley area totaled roughly one third of Maiden County's developed acres.

Historical and secondary source data may not always be as accurate as we would like to believe. Nonetheless, it is not the intention of risk and uncertainty analysis to call into question every piece of information ever published. Clearly, there are times when we will have the best data that are ever going to be available. When that is the case, they can be used without qualification. When the best available data are not very good, the data should be qualified.

The acid test for when to address the uncertainty in our information comes back to the question of how important is the data to our analysis. We'll never get a better estimate of the acreage of the county; more importantly, it is a trivial detail. It doesn't matter a bit if the actual acreage is 15,448 or 13,678. The same may not be true for the foundation information, or the interior drainage areas of tributaries. As a general rule, we recommend displaying the tentativeness of our knowledge routinely. This will, with time, help condition analysts, higher authority, and the public to understand the fact that analysts are not omniscient. When the tentativeness of our knowledge could have a significant effect on project formulation, it is essential to present that tentativeness.

Not all situations of uncertainty can or should be presented as a range of possible values. The following is an example of an issue that could be significant for plan formulation. It is described without recourse to values or ranges:

> The existing flood control system in the Heck Valley has a history of subsidence, instability, and seepage problems resulting from settlement caused by abandoned sub-surface coal mines, poor foundation conditions, and unsuitable fill material used in levee construction. These problems continue at the present time. The Heck Valley Comprehensive Study documented the problem areas and identified additional work needed to restore the existing system to the condition necessary to provide the original design level of protection. The recommended work is essentially the provision of stability berms and seepage control structures and is expected to be completed in 1990.
>
> The best engineering judgment is that the work currently underway will correct the problem through 2090, the duration of the planning horizon. It is nonetheless conceivable that in an area that already has a history of subsidence problems a new or related subsidence problem could arise at some point over the next 100 years. Subsidence is an issue of critical importance to plan formulation. A recurrence of the subsidence problem could affect the performance/reliability of the freeboard ranges of the project. Given a commitment to maintain the existing project, additional subsidence will mean additional project costs over the life of the project to address the problem.
>
> Unfortunately, the likelihood of a future problem, its extent, its effect on

project performance, and the cost of repair are unknown. The best engineering judgment available indicates that the stability problem will be solved by the work underway.

The message is simple. Our engineers think the problem is solved. Maybe it's not. The latter possibility will be looked at during the planning process.

Future Conditions

Forecasting future conditions with and without a plan is fundamentally an exercise in risk and uncertainty assessment. The primary risk and uncertainty objective in this step is to identify those key variables and assumptions that could significantly affect plan formulation. Some of these variables and assumptions will be buried deep in the mind and decisions of the analysts. Others will be evident in the report. In subsequent sections, examples of the kinds of variables the analyst is concerned with will be plentiful. For now, a few Heck Valley examples made evident in the report will be focused upon.

The following is an example of how part of a without-project economic condition could be described. Phrases indicating a lack of certainty have been italicized.

> It is *anticipated* that the economy of Maiden County will continue to diversify and experience moderate growth rates in the basic industries. Maiden County population is projected to increase *from 10-30 percent*, depending on the source of the estimate, over the 1970-2020 period. Study area population is projected to increase *by 1-5 percent* over the same period. This lower rate reflects the limited amount of land available for development in the study area. It is *anticipated* that the 200 acres of developable land will be fully developed *within the next 25 years*.
>
> There is *some possibility* that future flooding could have a negative impact on the local economy. It is *widely expected* that future flood events will not be met with the same level of Federal and State relief that occurred in 1982. One direct result of this could be the loss of some local businesses and a decline in housing stock. The extent of these losses *cannot be determined with any precision*.
>
> Given the strong ethnic community ties, the relative lack of affluence and an absence of any developable land in the immediate vicinity, *the potential* for a flood-induced "exodus" from the study area *is considered to be minimal*. The importance of such an exodus lies in its impact on future stage-damage relationships. Abandonment of buildings *could* mean a stage-damage curve based on full development of the floodplain would be overstated. However, if a project prevents the flood that would cause the exodus, it becomes an academic argument about whether or not the without-project condition stage-damage curve would be less some years into the future than it is at the time a project might be constructed. The loss of the businesses, their jobs, production and income would be prevented. Coupling this with the relatively minor extent of exodus considered possible, the without-project condition is effectively considered to be a constant level of development.

This description of Heck Valley again presents a range of possible values for population. It qualitatively treats other variables like growth. Words like "anticipated" and "possibility" reenforce the point that our knowledge is tentative without doing any damage to the presentation. Under the without-project condition, the possibility of floods having a negative impact on the economy beyond the damages caused is described as uncertain. The issue is subsequently dismissed as of minimal concern. If the analyst thought an exodus in response to a flood was a real possibility, it would be advisable to estimate the probability of such an exodus occurring before the project is built and adjusting benefits consistent with that analysis.

In a previous section, the Heck Valley report indicates that an existing levee problem has been fixed. The following section from the future without-project conditions section of the report considers this issue again.

> The existing Federal flood control system in the Heck Valley has experienced subsidence instability and seepage problems in the past. It is assumed that the rehabilitation work recommended in the Comprehensive Study will be completed in 1990 and that this work solves the existing system's stability and seepage problems for the remaining life of the system. It is expected that subsidence of the levee system will continue, although at a somewhat lower rate, and that it is neither engineeringly feasible to predict nor design for these occurrences. It is further assumed that the additional loading due to the proposed raisings will have an insignificant influence on the initiation or rate of additional subsidence.
>
> Although the most probable future condition is that the integrity of the existing system will be assured at design levels, that is not the only possibility. Subsidence instability could reoccur at any time. Continued subsidence calls into question the performance of the existing system, particularly the performance of the existing design freeboard. Performance of the improved project and its freeboard are likewise uncertain, as would be the costs of constructing any levee-raising or other alternative that would be subjected to possible continued subsidence. Subsidence is identified as a critical variable in project formulation.

In following the earlier existing condition description, this forecast goes the next logical step. It states the most likely future condition, but makes clear the simple fact that we cannot be sure what will happen in this known problem area over the next 100 years. It identifies this issue as important to plan formulation and preserves an alternative to the no levee subsidence future--one that provides for continued levee subsidence problems. Because this has been identified as a critical variable, it must be evaluated later in the report.

The description of the most probable future with the project would likewise provide an opportunity to identify significant issues as seen below.

> A flood control project would obviously reduce the damages from some flood events in excess of the existing project's design flow. Damages from some single event occurrences would be reduced from hundreds of millions of dollars to effectively zero. Regardless of the ultimate level of protection, however, there will

> be a residual flood problem. Flood damages from these events will be unaffected by a new project.[1]
>
> If a project is built at Tonsking, it will reduce expected annual damages at that location. However, it is anticipated that any levee/floodwall-raising alternatives could cause induced flooding at a number of communities that will not be protected by this plan. Thus, some Tonsking projects may be creating new flood risks or altering existing risks for some communities. This induced flooding is a major formulation issue.

In this example, induced flooding is identified as a major issue. Risks to the Tonsking community can be lessened at a cost of increased risks to other communities.

Assumptions about the induced flooding and subsidence variables must be identified for the most probable with-project condition as well. The following section excerpted from the with-project forecast makes the operating assumptions clear while identifying alternatives to the most probable future assumptions.

> Induced flooding is assumed to be minor in nature and of no significance to formulation. It is also assumed that the subsidence problem has essentially been corrected and there will be no minimal subsidence if a new project is built. One important result of this assumption is that floods in the freeboard range of the existing and improved projects can more reasonably be expected to be safely contained. This means that the existing flood problem is not as severe as it would be if freeboard were not as effective, thus expected annual damages without the project will be lower. It also means the improvement will provide more protection than it might otherwise have. Thus with this scenario, expected annual damages with the project will be lower. The overall effect of this assumption, from the standpoint of benefits, is to lower project benefits.[2]

---

[1] In many cases, it's possible that a new project could increase damages for certain events. A levee or floodwall could significantly increase the duration of flooding in an area that was previously unprotected. These barriers, once over-topped, function like an impoundment and can hold water on land long after it would have runoff. This is not likely to be much of a concern in the current instance because the existing levee system already causes this affect. Any change in the impounding effect would be of marginal importance to formulation and economic feasibility and would not warrant the work necessary to incorporate the effect of duration of the flood flows of such extreme events. Nonetheless, the possibility of alteration of risks is something that needs to be carefully evaluated in flood control studies.

[2] Bear in mind that this statement pertains to the Heck Valley project. Suppose that 50 percent of the damages that could result from flows in the freeboard of the existing levee are considered benefits to the existing project and not counted among existing expected annual damages. Likewise, 50 percent of the damages in the improved freeboard range are considered benefits to the project. The "benefits" "lost" in the existing freeboard will almost certainly exceed the "benefits" "gained" in the new freeboard because the flows in the existing freeboard are more frequent than those in the new

On the cost side, the assumption of a solved problem obviates the need for future expenditures of funds to address the problem. Recent stabilization work in Heck Valley cost $35 million. If this is a once-and-for-all expense, there is no need to estimate the costs of periodic stabilization work over the life of the project. Thus, while the assumption of no subsidence lowers benefits, it also lowers costs.

An alternative to the above future condition obviously centers around the subsidence assumption. It is the current judgment of the Engineering Division that there is no reasonable way to forecast the extent or rate of subsidence over the next 100 years short of foundation explorations, which are clearly infeasible due to prohibitive costs.

Although it may be impossible to predict the precise nature of the subsidence problem, it is not difficult to anticipate the results of a continued subsidence problem. Higher expected annual damages, both without and with the project, would occur due to less effective freeboard. Project costs would be higher. These issues will be taken up in the evaluation of alternative plans.

Another alternative to the most likely future is that the induced flooding problem will be far more serious than anticipated. This could lead to considerable public opposition by the residents of the affected communities now and/or lawsuits, court challenges, and mitigation work in the future. This alternative future condition is independent of the subsidence issue[3] and could occur with either of the two conditions described above.

While much of what has been described to this point is rather subtle in appearance, the cumulative effect on the approach to planning is rather radical. During this step of the planning process, it is important for the analyst and decision-maker to take stock of the risk and uncertainty analysis to this point. The first, and perhaps most critical, risk management decision needs to be formally presented in a coherent fashion. This can be done quite simply as shown in the following example.

KEY VARIABLES AND ASSUMPTIONS

The preceding description of the with- and without-project conditions rely on forecasts of future conditions and events that cannot be known with complete certainty. Of the many assumptions made and variables considered, two emerge as critical to project formulation. The first key variable is subsidence. It has been assumed that the levee subsidence problem has been solved for the duration of the

---

freeboard.

[3] In fact, flows contained in the freeboard range may be very relevant to the induced flood problem. In this example, the independence of the alternative to the subsistence issue is assumed for simplicity.

planning horizon. Of particular concern is the effectiveness of the freeboard and potential increases in project costs if this assumption is wrong. The second variable is induced flooding. The extent of this problem is highly uncertain because the data available for communities outside Heck Valley is of significantly lesser quality.

The example points out two significant issues without detailing the precise nature of the uncertainty. Subsequent sections will illustrate methods for dealing with these issues.

The idea of identifying key assumptions and variables is one that can be effectively adopted throughout the study process whether it appears in the report or not. Every analyst involved in the study would do well to develop such a list for each significant work task. This practice would provide a basis for considering legitimate ways to alter the plan or to reinvestigate plan effects. It also provides the basis for developing a comprehensive list of significant areas of uncertainty or risk issues to be used in determining what is and what is not important to formulation.

Consistent with this approach, it is not only feasible, but desirable, that such key assumptions and variables identify parameter and model uncertainty when it is important.[4] There is no shame in using less than the best information when there is neither time nor money for improving the data. The shame is in misrepresenting the quality of the data available, inadvertently or otherwise.

FORMULATION OF ALTERNATIVE PLANS

The first step in the plan formulation process during the initial stages of the study was to identify a range of engineering and management measures that could potentially address the planning objectives presented in the previous section. Table 3 lists the measures considered during this part of the study. Each of the measures was then evaluated based on engineering feasibility and cost-effectiveness. Some of the measures were obviously not appropriate for the specific problems of the study area and were quickly eliminated from further consideration based on professional judgement. For other measures, a more detailed analysis was required.

Initial formulation judgments and decisions are among the more critical risk management decisions typically made in a study. When many alternatives are under consideration, the level of detail and the quality of information is not what most analysts and decision-makers would like.

---

[4] Planning studies are a long way from the day when a report can admit the best flood profiles available are not very good--that we must choose between parameters that match the larger flows and those that match the smaller flows. It seems unimaginable today that a report could point out that the depth-percent damage curves were not field verified and that their accuracy is unknown. Yet all analysts know that these, and hundreds of other examples, are often the case.

Analysts are doing state-of-the-art work, and there is no need to hide the truth from other analysts or decision-makers. There is a real fear that openly admitting the tentativeness of our knowledge and the weak points in our analysis will be providing project opponents, within and without the system, with the ammunition they need to make it even more difficult to get projects built. So, until the day comes when we can openly admit what we all know, i.e., we are not omniscient, we must be satisfied with small improvements.

• Measure	• Reservoirs
• Levees (landward, riverward, straddle)	• Fish & Wildlife Conservation/Enhanceme Measures
• Channel Modification (including river dredging, limited channel excavation, island removal, clearing of vegetation.)	• Recreation Measures (including jogging and bike paths, boat ramps, hiking trails, nature and exercise stations.)
• Flood Warning & Temporary Evacuation Plans	• Closure Structures
• Acquisition and Demolition of Structures	• River Diversion
• Structure Raising and Floodproofing	• Elimination During Initial Evaluation Studies
• Flood Plan Regulations	• Flood Insurance

Table 3: Measures Formulated and Evaluated During Initial Planning

Nonetheless, a decision about what alternatives to consider in detail must be made, often before the best data are available. In the initial stages of formulation for Heck Valley, all dollar values were expressed in constant dollars (October, 1989). The initial decision process focused on the economic feasibility of alternatives. Different levels of confidence in the alternatives' costs and benefits were directly addressed.

Estimates of first costs of construction were made with varying degrees of certainty about project quantities and unit costs. The estimates were originally presented as point estimates of costs as shown in Table 4. Table 4 is the typical presentation format for comparing the economic effects of alternative plans. The table itself implies a degree of certainty in the numbers, which clearly does not exist. Based on this type of result, it would be likely that the Lake Floyd alternative would be carried forward for detailed study. In fact, from an economic perspective, it looks like the most promising alternative.

In reality, the benefit and cost estimates have some probability distribution. Although the probability distributions are unknown, they were assumed to be either normal, truncated normal, or truncated lognormal distributions.[5] Table 5 summarizes the assumed distribution parameters of both costs and benefits for the first costs and annual benefits for the alternatives considered in the initial stage of formulation.

[5] The normal distribution was used for Lucille costs and benefits, and Roland Park benefits. The truncated lognormal distribution was used for Lake Floyd costs. The truncated normal distribution was used for all other costs and benefits.

Alternative	First Costs	Annual Costs*	Annual Benefits	BCR	Net Benefits
Roland Park	$ 546.0	$ 47.1	$ 7.8	0.17	$-(39.3)
Lake Floyd	480.0	41.4	59.0	1.42	17.6
Lucille	123.0	10.6	4.4	0.41	-(6.2)
Levee Raising	99.0	8.6	8.1	0.95	-(0.5)
Dredge River	605.0	52.2	11.9	0.23	-(40.3)
Remove Islands	41.0	3.5	1.6	0.45	-(1.9)
Clear Islands	2.0	0.1	0.8	5.80	0.7

* 8.625% interest, 100-year project life. No O&M.

Table 4: Typical Presentation of Economic Effects of Alternative Projects

The information reflected in Table 5 more accurately depicts the state of knowledge about these alternatives. Costs and benefits could assume any number of possible values over a range with varying probabilities. Any analyst would be expected to feel more comfortable expressing costs and benefits as likely to fall in some range rather than to assume a specific value, particularly with the type of data typically available during initial formulation.

Although the values in Table 4 appear to reflect the analysts' best estimate of the most likely costs and benefits, the simple act of constructing a hypothetical distribution like that revealed through Table 5 produces a considerably different result. The expected value of the distributions with the noted parameters need no longer be the "best guess" value used in the traditional analysis of Table

Alternative	Mean	Standard Dev.	Minimum	Maximum
FIRST COSTS:				
Roland Park	$ 546,000	$ 182,000	$ 450,000	$ 1,000,000
Lake Floyd	480,000	200,000	450,000	1,500,000
Lucille	123,000	41,000	NA	NA
Levee Raising	99,000	15,000	60,000	180,000
Dredge River	605,000	120,000	450,000	1,100,000
Remove Islands	41,000	15,000	30,000	100,000
Clear Islands	1,600	500	1,200	5,000
ANNUAL BENEFITS:				
Roland Park	$ 7,800	$ 2,600	NA	NA
Lake Floyd	59,000	21,000	$ 10,000	$ 65,000
Lucille	4,400	1,500	NA	NA
Levee Raising	8,100	1,500	7,000	20,000
Dredge River	11,900	2,500	7,500	25,000
Remove Islands	1,600	700	1,000	3,000
Clear Islands	800	150	300	2,000

Table 5: Assumed Distribution of Costs and Benefits for Alternative Plans ($1,000's)

4. For example, the analysts' estimate of the most likely cost of the Roland Park project is $546 million. Dividing the difference between this "mean" and the largest conceivable cost anyone offered

Alternative	First Costs	Annual Costs*	Annual Benefits	BCR	Net Benefits
Roland Park	$ 632	$ 54.6	$ 7.8	0.14	$-(46.8)
Lake Floyd	561	48.4	48.6	1.00	0.2
Lucille	123	10.6	4.4	0.41	-(6.2)
Levee Raising	99	8.6	8.7	1.01	0.1
Dredge River	628	54.2	12.1	0.22	-(42.1)
Remove Islands	47	4.1	1.8	0.44	-(2.3)
Clear Islands	2	0.2	0.8	5.20	0.6

* 8.625% interest, 100-year project life. No O&M. BCRs may differ due to rounding.

Table 6: Presentation of Economic Effects of Alternative Projects Using Interval Estimates of Costs and Benefits (Millions of 10/89 Dollars)

for this project by four[6] yielded an estimated standard deviation of $182 million. These two values describe a normal distribution.

The expected value of a truncated normal distribution as described for Roland Park in Table 5 is $632 million, significantly more than the original $546 million. Thus, when we take the analysts' level of confidence in their own numbers explicitly into account, we can obtain a significantly different result. Table 6 presents revised estimates of the values in Table 4 using the expected values of the distributions described by Table 5 and the above footnotes. According to Table 6, Lake Floyd looks like a far less appealing alternative than it did in Table 4. These new values, however, represent nothing more than another point estimate.

To understand the full range of possible results with each alternative, it is necessary to

[6] The analysts were asked to identify reasonable estimates of the minimum and maximum costs for this project. The analysts felt the minimum cost would be about $450 million (surely not a negative or small number as would be possible with a normal distribution as described above), with the "realistic" maximum cost $1 billion. The difference between the mean and this maximum was divided by four to obtain an estimate of the standard deviation (see the discussion of sampling in this case study for an explanation of this step that estimated the standard deviation). The normal distribution described earlier was truncated at these values. The truncated normal distribution reflects more of the analysts' uncertainty and preserves more information about the estimate than does the information in Table 4.

Alternative	Expected Value	Minimum	Maximum	Probability BCR>1.0
Roland Park	0.15	0.00	0.41	0.0000
Lake Floyd	0.90	0.11	1.64	0.3935
Lucille	0.41	0.16	0.95	0.0000
Levee Raising	1.04	0.56	2.11	0.5139
Dredge River	0.23	0.10	0.45	0.0000
Remove Islands	0.47	0.15	1.08	0.0037
Clear Islands	5.43	1.88	11.14	1.0000

Table 7: Distribution of Benefit-Cost Ratio

consider what might happen if low cost circumstances are realized when benefit estimates prove to be greater than expected. Such circumstances would indicate a greater likelihood of economic feasibility and a greater return on the investment. Other circumstances might result in costs higher and benefits lower than those presented in, say, Table 4.

A 4,000-iteration simulation was performed for each of the alternative projects. In each iteration, a value was randomly selected from the distributions of first costs and annual benefits shown in Table 5. First costs were converted to annual costs and the resulting BCR was computed. Thus there were 4,000 cost estimates, 4,000 benefit estimates, and 4,000 benefit-cost ratios computed. The distribution of all the possible benefit-cost ratios is summarized in Table 7.

The information in Table 7 provides considerably more information than that found in Tables 4 or 6. For example, note that each alternative has a mean BCR. This is the single number that can be reported, as has traditionally been the case. There is no necessity to present a range of numbers. One number can still be reported. That number reflects more information than any other single number thus far reported. In essence, the mean BCR obtained from this simulation suggests to let costs and benefits vary randomly and independently (although independence is not a requirement), as our experts think is reasonable, and the most likely BCR is now the mean of the distribution obtained from this simulation.

The table also includes a minimum and a maximum value that the BCR obtained in the simulation. The table shows that several alternatives will not likely be justified regardless of how costs and benefits ultimately turn out. Significantly, it is demonstrated that Lake Floyd, once the prime alternative, could have a BCR as low as 0.11 or as high as 1.6. The expected BCR, allowing costs and benefits to vary rather than assume one and only one value, is now 0.9 rather than 1.4.

Alternative	Mean	Standard Deviation	Coefficient of Variation
Roland Park	.148	.057	.385
Lake Floyd	.903	.320	.354
Lucille	.410	.132	.311
Levee Raising	1.036	.208	.201
Dredge River	.230	.058	.254
Remove Islands	.469	.170	.362
Clear Islands	5.426	1.511	.278

Table 8: Relative Risk of Alternatives - Coefficients of Variation

Furthermore, the probability that the Lake Floyd project is economically justified is 0.3935,[7] whereas Table 4 gives the appearance that justification is a certainty.

Neglecting island clearing as a complete solution due to its minimal impact on the flood problem, levee raising arises from this analysis as the most feasible alternative. First, its expected BCR is 1.03. The minimum value of 0.6 is higher than that for Lake Floyd. The maximum value is 2.1, significantly higher than the "seemingly-certain" value of Table 4. Perhaps most importantly for making a decision about where to commit resources in detailed further study, the probability of a justified project is 0.5139.

Table 8 presents a measure of relative risk. While the mean is often regarded as the best estimate of a value, the variation in a distribution of values is likewise important for good risk management. The standard deviation is a common measure of the variation in possible outcomes. Levee raising has a standard deviation larger than four other alternatives. This alone is not a reliable risk measure. For example, when one project is much larger than another, it will normally have a larger standard deviation without necessarily being more risky.[8] A measure of relative risk is obtained

---

[7] In 39.35 percent of the 4,000 iterations, the estimated BCR was 1.0 or greater. This result, as well as all the others, is only as good as the assumptions and logic that the simulation model is built upon.

[8] Turning from the benefit cost ratio for the moment, if a project has expected benefits of $1 million and a standard deviation of $1,000, it is less risky than a project with expected benefits of $1,000 and a standard deviation of $500. The relative variation for the larger project is much smaller, though the absolute risk is twice as large.

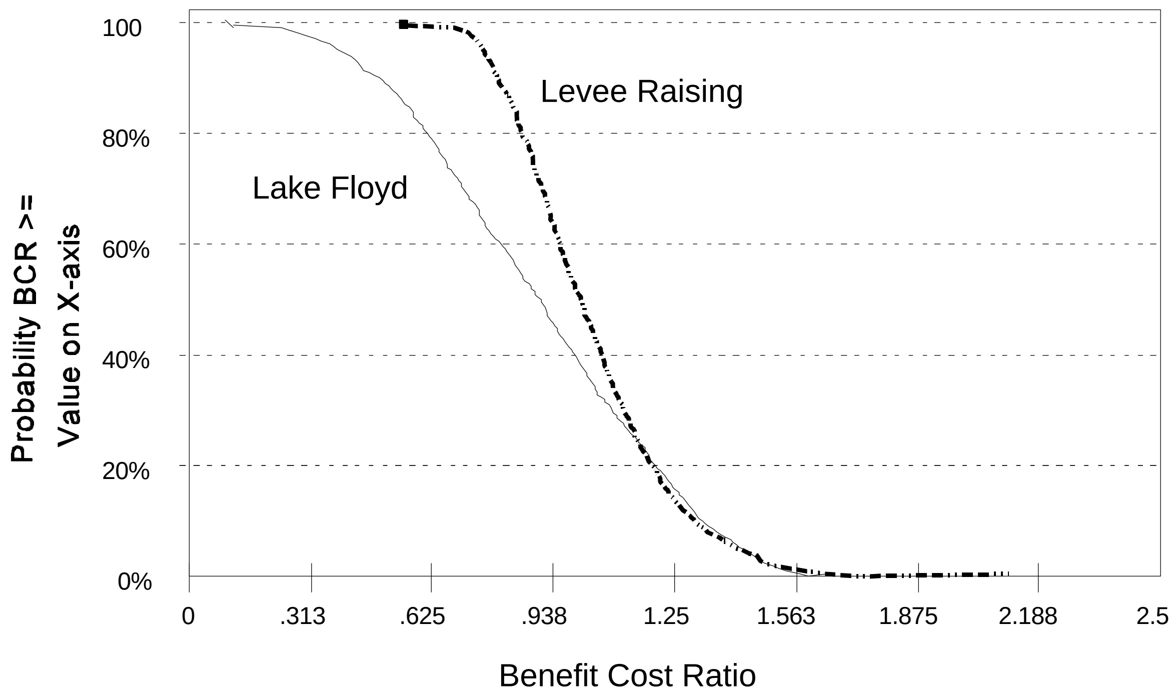


Figure 1: Comparison of BCR Cumulative Distributions - Lake Floyd vs. Levee Raising

by dividing the standard deviation by the mean.[9] In Table 8, the means and standard deviations shown are for each of the alternatives' benefit-cost ratios. The largest standard deviation is for the island clearing project. Rather than being the riskiest project, based on the relative risk measure obtained from the coefficient of variation, it appears to be the second least risky project. Once again, the levee-raising project ranks as the least risky project.

Developing the risk and uncertainty assessment described in the paragraphs and tables above is the first part of the analysis. Decision-makers must make a decision about which project to pursue for further study and possible implementation. This is another major risk and uncertainty management decision. The question is whether to pursue the Lake Floyd Reservoir or the levee raising. The island clearing alternative is not considered a stand-alone alternative because it results in an unacceptably high residual risk and does not contribute significantly to the planning objectives.

The information presented in the risk and uncertainty assessment indicates that the levee raising project has the highest likelihood of being justified. Figure 1 presents a direct comparison of the distribution of possible BCR's for the Lake Floyd and levee-raising alternatives. The cumulative distributions show that levee raising consistently has a greater probability of a benefit-cost ratio equal to or greater than any value from 0 to about 1.2. Lake Floyd is more likely to produce a BCR in the range from about 1.2 to about 1.4. BCR's greater than 1.4 are more likely to result from the levee-

[9] This is also known as the coefficient of variation.

raising project.[10] As noted previously, there is a 60 percent chance the reservoir will not be economically justified, while there is only a 49 percent chance the levee-raising project will not be justified.

A traditional analysis (based on Table 4) without any risk and uncertainty analysis would lead to a decision to pursue the reservoir project on economic grounds. A more detailed analysis, using risk and uncertainty analysis, favors the levee-raising project. Coupling this economic analysis with the substantial environmental objections to a large reservoir project, the levee-raising project will be carried forward for additional study, while the reservoir will not.

The contributions of the alternatives considered to the planning objectives, specifically those pertaining to risk and uncertainty analysis, confirm this decision. Reservoirs create the risk of dam failure. This risk of failure may in reality be less than the induced flooding risk to other communities created by levee raising. Nonetheless, it is certainly more controversial. The potential for loss of life from a dam failure far exceeds the risk from either a levee failure or induced flooding. River dredging actually minimizes the threats to human life and the creation/transfer of risks. Unfortunately, it results in great risk to the environment and is subject to significant performance uncertainty.

The best data are available for the levee-raising alternative. The reservoir is subject to considerable uncertainty about foundation conditions and relocations, both of which are major cost items. Benefit estimates are also suspect for areas other than Heck Valley and categories other than inundation reduction due to lack of data. Dredging alternatives are subject to considerable engineering and cost uncertainty because the alternatives require dredging 12 feet of material from 25 miles of river. The integrity of the levee systems, in light of the subsidence problem, could be insured only through the construction of large and expensive stability berms that would significantly reduce the channel cross-section. Thus, additional study would be expected to result in even higher expected cost estimates.

It is anticipated that each of the major alternatives could achieve an acceptable level of risk in the Heck Valley. The reservoir creates what may be regarded as an unacceptable risk of dam failure for some communities, perhaps as a result of an emotional exaggeration of the possibility of a dam failure. Levee raising has the potential to create an unacceptable risk for other communities, though the most probable with-project condition forecast is that this will not be the case. River dredging does not result in dam failure or induced flooding risks. It does, however, result in the possibility of loss of protection from the existing system if stability problems threaten the integrity of the existing system.

The judgement of the initial formulation process is that the most efficient and effective means of increasing the level of protection in the currently protected communities is to raise the height of

---

[10] If the cumulative distribution of levee raising BCR's was everywhere above the cumulative distribution of the reservoir's, the levee-raising alternative would be said to stochastically dominate the reservoir (see the Expected Utility Theory Appendix for further discussion). In the current case, there is no stochastic dominance because the reservoir could result in more likely BCR outcomes over a limited range.

the existing system by additional levees and floodwalls. Plans using these two measures were developed for each of three levels of protection, i.e., 290,000 cfs, 343,000 cfs, and 450,000 cfs. The 290,000 cfs discharge represents the minimum practical discharge for which raising could be accomplished, approximately 2 feet; the 343,000 cfs flow is equal to a flood produced by a regional storm the magnitude of Hilda and the 450,000 cfs flow is equal to the estimated Standard Project Flood (SPF).

Intermediate levels of protection can be considered based on interpolation of data from the three levels of protection considered in detail. The kind of measure (i.e., levee or floodwall) and orientation used to raise a specific section of the existing system (landward, riverward, straddle) were determined based on planning objectives, engineering feasibility and economic efficiency, minimizing wherever practical significant disruptions of existing structures, roads, utilities, or environmental resources.

The initial formulation discussion above was based on protection of the entire Heck Valley. Focus on the entire valley permitted us to consider a range of different alternatives. The focus of the case study will shift at this point to consideration of a plan for the hypothetical town of Tonsking. The exposition will be significantly simplified by focusing on one community rather than a series of communities. The analyses presented for Tonsking would essentially be repeated for each of the communities and the results aggregated for reporting purposes. In actuality, it may be necessary to conduct a more complex aggregation of the analysis, depending on the extent of interdependencies among the communities.

EVALUATION OF ALTERNATIVE PLANS

The Heck Valley study evaluation of alternative plans centered around the economic analysis. Economic analysis of flood control projects, as practiced by the Corps, provides a prime example of risk assessment. The probability (flood frequency) and consequence (flood damages) of the flood hazard are conjoined to estimate a mathematically expected risk (see Chapter 2 of the Manual for Risk and Uncertainty Analysis in Corps' Civil Works Planning) called expected annual damages (EAD). The estimation of EAD is the primary focus of this section.

The exposition begins with a discussion on sampling to describe how statistical sampling can contribute to risk and uncertainty analysis. It is followed by a discussion of the general uncertainty present in a stage-damage estimate. There is an abbreviated discussion of uncertainty in the H&H work followed by an estimation of expected annual damages drawing on all the above factors to address the handling of cumulative uncertainties.

Sampling Program

Methods for estimating residential flood damages vary from district to district. When time and money permit, damage surveys of the entire floodplain are preferred as they eliminate any possibility of sampling error. In many cases, a survey of the population is not possible and a sample of the population is needed. The following example is based on the need to estimate the average value of a structure in the floodplain.[11,12] A sample program is described, some results derived and their significance is discussed.

There are 8,319 residential structures (by our count) in the estimated probable maximum flood (PMF) floodplain. There is neither time nor money for a complete survey of the floodplain. A sample is required. It is common practice within the Corps to consider the time and money that is available and determine the sample size based on the available resources without regard for the amount of information contained in the sample. A ten percent sample is frequently chosen because it is a nice round number and it appears to be reasonable. The information obtained from the 10% sample, however, may not be as accurate as the analyst may intuit. Alternatively, it may be possible to get the information with nearly the same degree of accuracy with a smaller sample.

The key considerations in designing a sample are: the number of structures in the population (floodplain), how accurate is the sample mean with regard to the true mean value, and the range of values that exists in the floodplain. Assuming a simple random sample[13] will be conducted and accuracy within ± $2,000 is desired, the following formula is used to determine the sample size.

$$(1) \quad n = \frac{N\sigma^2}{(N-1)(B^2/4) + \sigma^2}$$

Plugging in the values N = 8,319 and B = $2,000 (where B is the bound on the estimation error), it is not possible to complete the calculation without a value for σ, the population standard deviation.

---

[11] Stage-damage curves based on a sample of flood plain development are developed in a number of ways. For example, a stage-damage relationship may be developed for a 10 percent sample. The resulting values can then be multiplied by ten to achieve the estimated relationship for the flood plain. Other approaches may estimate the average structure value for the flood plain or a segment (strata) thereof. This mean is then used as an estimate of the value of each house in the flood plain and is an input for the depth-percent damage curve for an individual structure. More generally, however, the sample data can be analyzed to provide more information than the point estimate of structure values alone.

[12] Sampling techniques similar to those described below can be used to estimate the value of structure contents for a floodplain or any strata thereof.

[13] A simple random sample will be illustrated because it is the most common sample and the easiest. In practice, it will almost always be more efficient (i.e., more information will be obtained from a smaller sample) to use a stratified random sample or a cluster sampling scheme.

A stratified random sample would divide the flood plain into subregions or strata. These strata could be based on flood risk, e.g, 10-year flood plain, 10- to 50-year flood plain, etc. Or the strata could be determined on the basis of property values, topography, exposure to waves, or any variable of importance in the particular analysis. A simple random sample is then selected from each strata. A cluster sample is basically a simple random sample where the items selected to be sampled are clusters of units. For example, we may actually sample entire blocks of structures rather than individual structures in order to minimize the cost of topographic surveys.

In the absence of knowledge about the value of σ, estimates can be used. These estimates may be available from previous studies, from test samples,[14] or by estimating the range in housing values that exists. In this case, discussions with local realtors and a review of tax assessments indicated the minimum structure value is about $10,000, the maximum value $130,000. This results in a range of $120,000.

A normally-distributed variable has close to 100 percent of all values fall within ± 4σ of the mean. In the absence of any information to the contrary, we assume a normal distribution of structure values and the $120,000 range represents 8σ. The standard deviation is estimated to equal $15,000. Plugging this value into equation (1), a sample size of 219 structures is obtained, consistent within the constraint of ± $2,000 of the true mean value. This is significantly less than the 832 houses that would result from a 10 percent sample.

It is worth noting that equation (1) can be used to estimate the bound on the error of estimation (B) for any sample size. In such a case, the sample size is plugged into the **n** value and we solve the equation for B. This would give the analysts an idea if their resource-determined sample size provides more or less information than was desired. Try this for a sample size of 832.[15]

The actual sample conducted in this case had 234 observations. There is no reason to disregard the additional information. In fact, n = 234 is expected to yield a bound on the error of

[14] A test sample is a small random sample conducted for the sole purpose of obtaining an estimate of the population variance and, hence, standard deviation.

[15] Your answer should be in the neighborhood of B=$990.

$1,933 rather than $2,000. Tax records provided a complete list of all structures in the floodplain. Each tax record was assigned a number from 1 to 10,000 (about 1,700 structures were outside the floodplain). A list of 5-digit random numbers was generated, and 234 structures

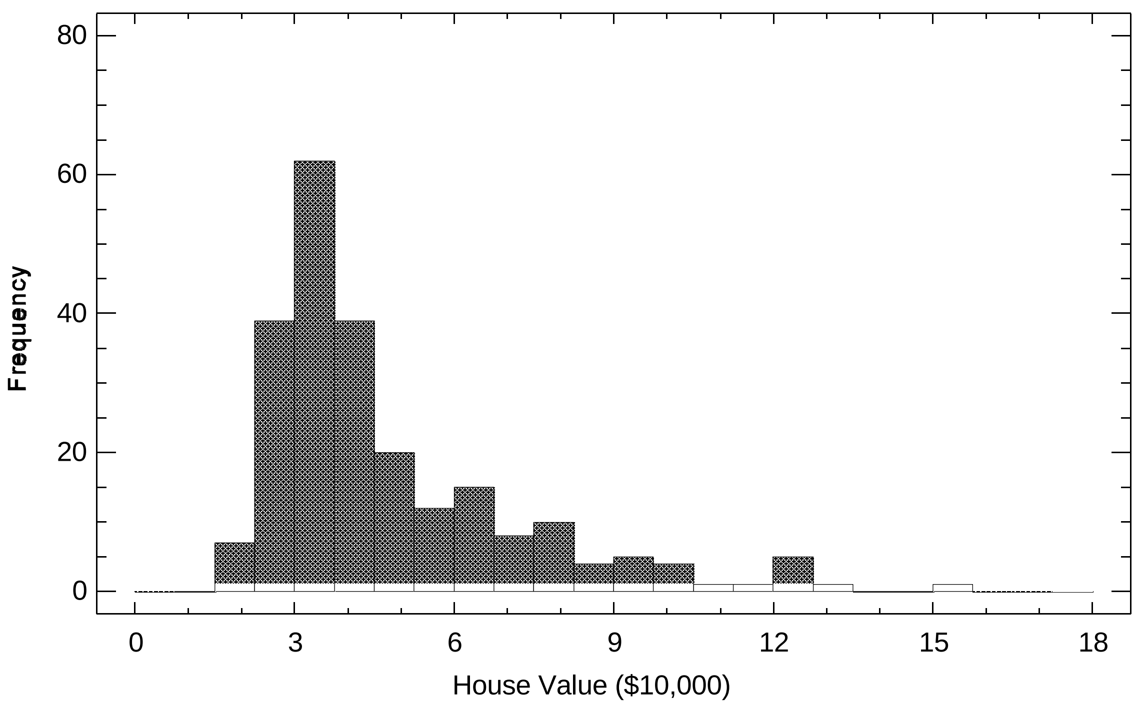


Figure 2: Residential Structure Value - Frequency Histogram

were selected.[16]

Statistic	Value
Sample Size	234.0
Average	47,655.2
Median	39,040.7
Mode	33,133.1
Geometric Mean	43,086.4
Variance	5.82058×10^8
Standard Deviation	2,4125.9
Standard Error	1,577.16*
Minimum	17,649.9
Maximum	154,734.0
Range	137,084.0
Lower Quartile	32,011.2
Upper Quartile	5,673.2
Interquartile Range	24,360.8
Skewness	1.70885
Standardized Skewness	10.6718
Kurtosis	3.00984
Standardized Kurtois	9.39824

Table 9: Structure Value Sample Descriptive Statistics

Figure 2 shows a frequency histogram of the structure values. It is not difficult to imagine that another sample would provide a different distribution. Table 9 provides descriptive data for the selected sample. The mean value is $47,655. It turns out that our original estimate of the maximum structure value was too low. However, that is of little concern at this point. Using the sample mean ± 2 standard errors ($1577), the 95 percent confidence interval for the average structure value is $44,501 through $50,809. Although this sample mean is $47,655, it is not likely that the same estimate would be obtained from taking another sample. However, 95 times out of 100 the sample mean would be between $44,501 and $50,809.

The significance of this is that if the value $47,655 is used, the damages may be understated (if structure values are closer to $50,809) or overstated (if structure values are closer to $44,501). This uncertainty exists regardless of the method used by the analyst in estimating damages. The point is quite simple, and it is important to realize that damages may be understated or overstated. No credible analyst would be more comfortable saying the average structure value is $47,655 than he would saying the average structure value is between $44,501 and $50,809.

This is an example of a case where the analyst does not know the structure value with

[16] For example, the first number was 7688. The structure with this number became part of the sample. The list of random numbers was selected from a uniform distribution of integers from 1 to 10,000. This insured the values did not exceed 10,000. In some cases, the structure selected in this manner was not in the floodplain, so it was disregarded and a new number was selected. Likewise one house number was selected twice. It was simply ignored the second time, and a new number was selected.

The numbers were assigned to the structures indirectly. A hardcopy printout of all properties on the tax rolls was obtained. There were 100 properties per page. Thus, to find the first entry, 7688, the 88th entry on page 77 (the first page contained entries 1-100, page 2 contained entries beginning with 101, etc.) was used.

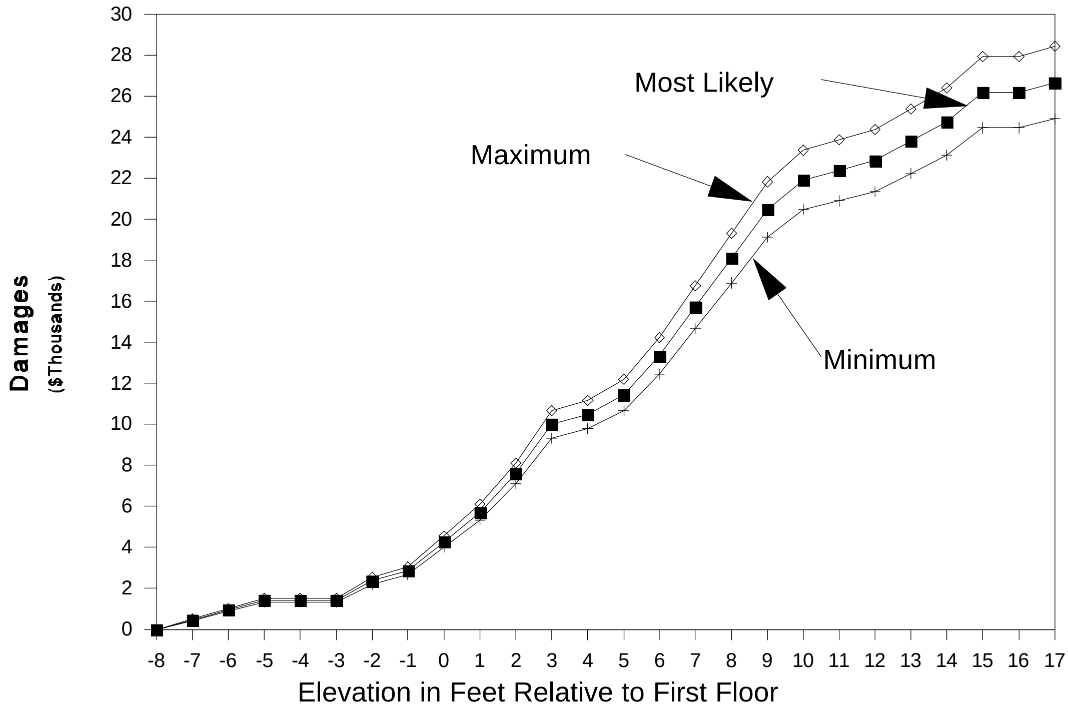


Figure 3: Stage-Damage Range - Single 2-Story Structure, $47,655 Value

certainty and the uncertainty can easily be preserved.[17] Figure 3 provides an example of a residential structure damage curve for a single two-story structure with a basement and market value of $47,655, along with the damages based on higher and lower structure values of $44,501 and $50,809, respectively. The figure graphically portrays the uncertainty in damage estimates that stems solely from uncertain structure value.

Stage-Damage Uncertainty

Analyses have, in the past, used point estimates of damages at various flood stages. For example, in Tonsking damages at 554.5 MSL would typically be reported as $742,877,000. It is commonly recognized that damages cannot be estimated this precisely. Because the stage-damage curve is one of the most important elements of a flood control analysis, it is important to preserve the information that is available to the analysts and to recognize and deal with the uncertainty inherent in the analysis. This example begins with some general discussion and proceeds to specific techniques for handling the problems.

To illustrate the use of risk and uncertainty assessment in the estimation of a stage-damage

[17] As a practical matter, this uncertainty can be translated to the stage-damage curve by using the mean value for each structure and running the programs which adjust the damages based on the structures' topographic data and flood problem and compile damages. Then the upper and lower limit on the estimate of structure value can be used to estimate damages at the possible extremes.

curve, this example will refer to an approach compatible with the Hydrologic Engineering Center's programs (SID and EAD). The principles illustrated in this example are applicable to other approaches as well.

To begin with, a stage-damage curve shows the relationship between dollar damages and the depth of water only. This curve is based on some set of assumptions about the values other relevant factors take and maintain without change. These factors include the duration of flooding, sediment loads, the presence or absence of toxic wastes in the flood waters, the presence of ice or debris, velocity of the water, waves, warning time, flood fighting efforts, etc. These and other factors can be extremely important in the determination of flood damages. Stage, generally considered the single most important determinant of damages in fluvial flood situations, is the only factor usually considered[18] in order to make the estimation problem manageable.

Where differences in the assumed values of these other factors can have an influence on the level of damages estimated at a given stage, it is important to take this variation into account. For example, if damages at a home with five feet of water on the first floor would vary from $5,000 to $8,000 (a 60 percent difference) depending on the duration of the flood (shorter floods causing less damage), it is important to preserve that information. While specialized techniques have been developed to deal with the presence of ice and wave attack, the point remains that the effect of significant differences in non-stage factors should be accounted for. It is common practice, not necessity, that only stage is considered in the damage function.

Restricting our attention to the stage-damage relationship, given a certain stage of flooding, there can be uncertainty about the value of property at risk (as was illustrated in the Sampling Program example above), the flood stages that cause damage to individual properties[19] and the individual structure's susceptibility to flood damage.

The value of property at risk is sensitive to the theoretical basis for value used. Market values, replacement in-kind (i.e., this is akin to a depreciated replacement), and capitalized annual income theoretically will result in the same property value. In practice, this does not happen.

---

[18] Everyone recognizes that a flood that lasts days and leaves behind a huge sediment load is more damaging than a flood that lasts hours with little sediment. Despite the complexity of this relationship, Corps' analysts make a necessary accommodation to reality and simplify the relationship to depth and damages. Wave damage in coastal flood zones and some lake fronts is one noteworthy and generally recognized exception to this rule of thumb. Expanding the damage relationship beyond the depth dimension is one avenue of research that could prove beneficial to analysts seeking more realistic estimates of damage relationships.

[19] Of particular interest are topographic data that relate to the first floor elevation of the structure and the point at which flood damage begins. This latter point is usually called the "zero damage point" (i.e., the greatest elevation to which water can rise and cause no damage to the structure) or the "ground elevation" (i.e., the lowest ground elevation surrounding the structure). Experience has shown that damage estimates are extremely sensitive to the zero damage point.

These different approaches to estimating property value will produce estimates of willingness to pay for flood control that may vary greatly. While all approaches have their advantages and disadvantages, the author finds that replacement in-kind most consistently measures the consumers' willingness to pay for flood control, given that we are to operates within the expected annual damage framework. The important point is that an improper or poorly-applied theoretical approach can result in gross exaggeration of values above or below the relevant value.

Given that a proper theoretical approach can be selected, the tool for measuring value[20] can often be unevenly or improperly applied. Nonetheless, assuming these difficulties can be overcome, there still remains substantial uncertainty in the estimation of value when sampling techniques have to be applied. Some of this uncertainty has been discussed above.

Once the uncertainty surrounding property values has been appropriately documented, damages for a particular structure are typically estimated based on some fixed percentage of structure value. The percentage of structure value varies with the type of structure.[21] Attempts to validate the generalized FEMA and District depth-percent damage curves in the field have generally failed, giving emphasis to the uncertainty inherent in estimates of this type. It may be useful to preserve the information possessed about flood damages and perhaps say that damages to a residential structure will vary from 3 to 8 percent for a given depth of flooding.

Given a two-story structure with a basement, valued at $47,655, the stage damage curve generated would depend on the depth-percent damage curves used by the analyst. There are many different depth-percent damage curves in use by Corps' analysts. Which is the true curve? We do not know for sure. In such a case, it is better to recognize and preserve our uncertainty than to pick one of these relationships and argue that it is <u>the</u> correct curve. Thus, damages with four feet of water on the first floor of this hypothetical house might range from, say, 20 to 28 percent of the structure value.[22] For a house valued at $47,655, this is an actual range of about $9,500 to $12,900.

Arguing that damages for this stage of flooding fall between $9,500 and $12,900 is far more realistic than stating that damages are $10,484. If $10,484 is indeed our best estimate of the resulting damage, that information can still be used, however, as will be demonstrated shortly.

---

[20] For example, comparable sales or tax assessments for market value, Marshall-Swift or similar valuation procedures for replacement in-kind, and capitalized rents all are subject to error by the user for a variety of reasons.

[21] Generally, houses are characterized by the number of stories and the presence or absence of a basement. In a few cases, the house is further differentiated by style (rancher, cape cod, etc.) or construction material (clapboard, masonry, etc.).

[22] Where possible, it is always best to use valid statistical techniques in the analysis. If the population of depth-damage curves is known, it may be possible to construct confidence intervals about the depth-percent damage curves. Most of the examples in this case study assume a lack of such information to remain closer to the Corps analyst's experience in most studies.

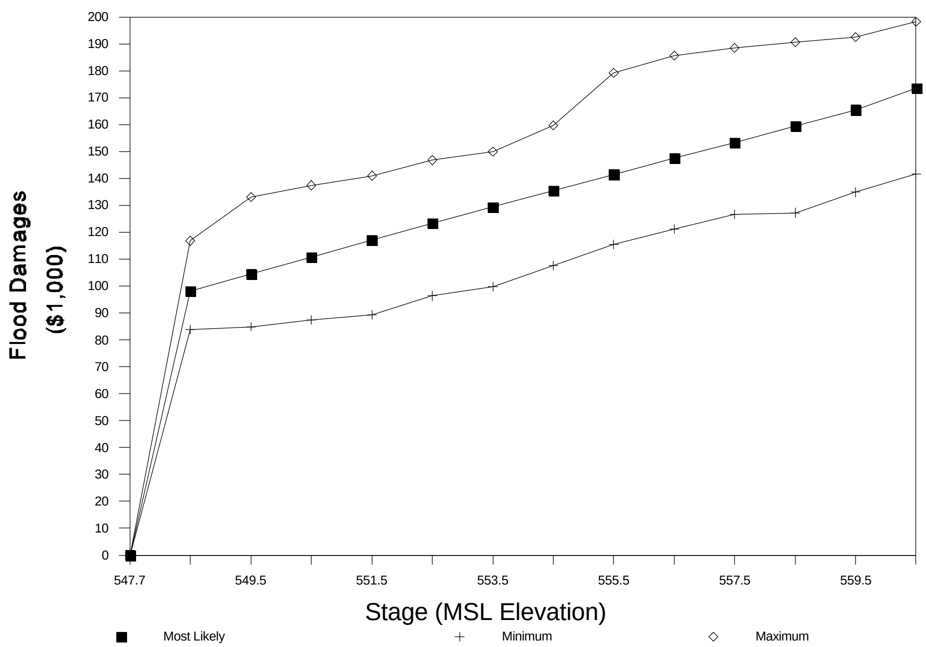


Figure 4: Total Residential Damages

Considering that the actual value of the average structure is uncertain (because of the value concept used and the estimation technique used to measure it), the damage caused by a specific depth of water is uncertain, and the effects of factors other than flood stage are largely ignored, it is not difficult to understand why stage-damage curves are far from determinate relationships.

Considering damage as a function of flood stage, the damage that occurs at a given flood stage is not known with certainty. Instead, flood damages at a given stage have a distribution. For example, Figure 4, depicting residential structure damages in Tonsking, shows that damages at a river stage of 554.5 MSL range from $107,700,000 to $159,800,000 and are most likely $135,500,000. Although the actual shape of that distribution will rarely be known,[23] Figure 5 depicts the concept for a hypothetical triangular distribution.

Damages at 554.5 MSL in this case use two basic pieces of information, the value of property and its susceptibility to flood damage (i.e., depth-percent damage curve). Once the range in average property value was established at $44,500 to $50,800 and topographic data for each structure was obtained, damages were estimated using the range in depth-percent values shown in Table 10. Thus, the minimum value for damages, $107,700,000, was based on average property values of $44,500 and minimum depth-percent damages. Maximum damages of $159,800,000 are based on property values of $50,800 and maximum depth-percent damages.

[23] Though it could be derived if the underlying distributions are estimated.

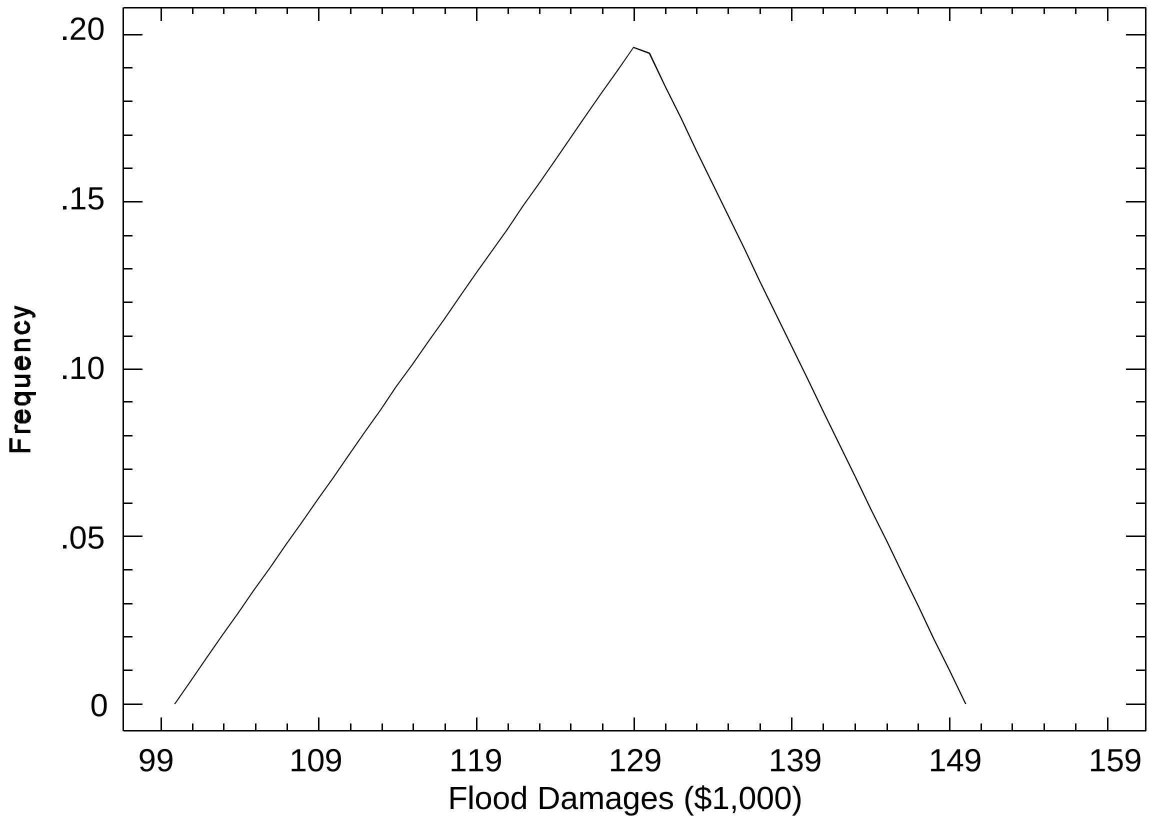


Figure 5: Residential Structure Damages at 553.5 MSL - Triangular Distribution of Damages

Most likely damages of $135,500,000 are, in essence, based on the type of damage curves Corps' analysts typically estimate.

While the actual distribution may not be known, it is usually possible to place some bounds of confidence on the damage estimate. The confidence bounds may not be statistical confidence limits, e.g., the "traditional" 95 percent confidence interval, nonetheless, it is possible, using professional judgment, to specify the minimum and maximum damage that could occur with a given depth of water. The damage estimate that is traditionally used can still be used as the most likely damage estimate.

To illustrate this last point, consider a common situation confronted during damage survey interviews to estimate damages to a commercial property. Inventories can vary dramatically with the time of year, season, month, or day. A produce wholesaler could lose its entire inventory if a flood occurs the day before orders are shipped to retailers. A flood the day after produce is

	Range in Damage as % of Structure Value		
Depth in Feet Below 1st Floor	Minimum	Most Likely	Maximum
-8	0	0	0
-7	0	1	1
-6	0	2	3
-5	0	3	4
-4	0	3	5
-3	0	3	6
-2	0	5	7
-1	0	6	8
0	3	9	11
1	9	12	18
2	13	16	20
3	18	21	26
4	20	22	28
5	22	24	33
6	24	28	41
7	26	33	44
8	31	38	49
9	36	43	48
10	38	46	50
11	40	47	52
12	42	48	57
13	44	50	59
14	46	52	60
15	47	55	60
16	48	55	60
17	49	56	60

Table 10: Range In-Depth Percent Damage Curves (Minimum - Most Likely - Maximum)

shipped may cause no damage if the produce inventory is zero.[24] A typical response would be

[24] This is not an uncommon occurrence. Many businesses have an extremely variable inventory. Tobacco warehouses house tobacco only a few months each year. They are empty the rest of the time. Greeting card manufacturers have several peak seasons where inventories can be many times the "normal" inventory.

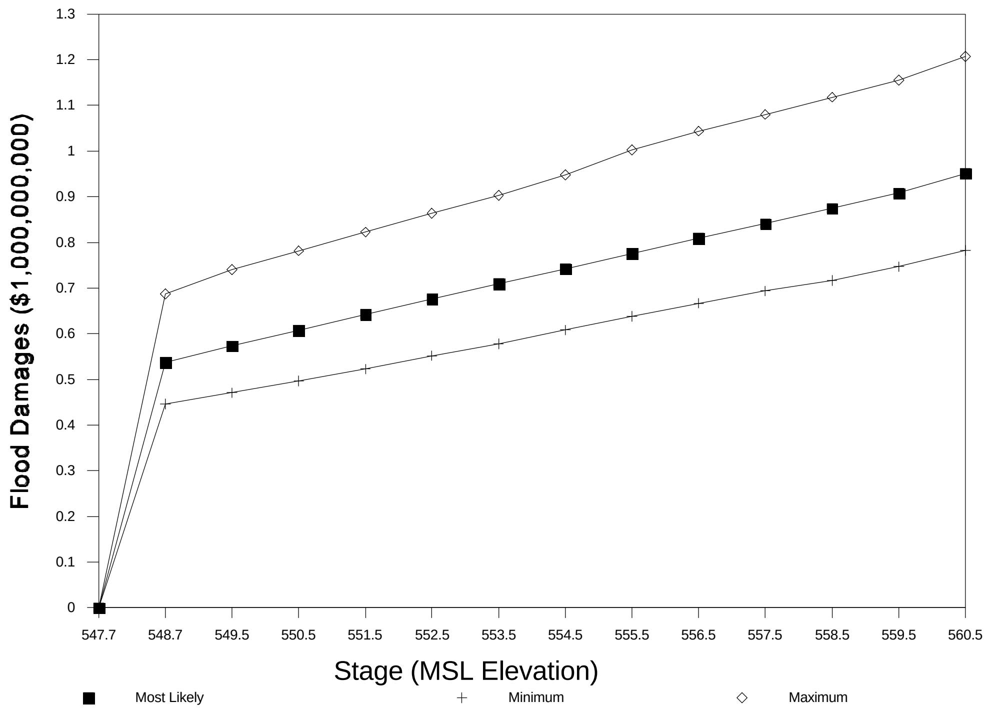


Figure 6: Stage Damage Curve - Tonsking

based on the most common inventory level or the average inventory level. Such assumptions could substantially over- or underestimate actual flood damages. It is preferable to note the minimum, maximum, and most likely level of damages at a given flood level and, furthermore, to use all of this information.

Figure 6 presents a most likely stage-damage curve for all flood damage in Tonsking, bounded above and below by a minimum and maximum curve. This figure indicates that potential flood damages for a stage of 554.5 MSL are distributed over a range from $608,500,000 to $947,700,000, with $742,900,000 the most likely value. These curves have been generated using the basic arguments outlined above and extending them to other categories of damages.

Damages can vary for a variety of other reasons unrelated to inventory levels or the characteristics of the flood itself. A flood at night with two hours warning will likely cause more damage to a business than the same flood during the day when all employees are present and available for flood fighting. Warning time itself is an issue. Damages will depend on the amount of warning time available to the business. Likewise, damages may depend on the availability of rental trucks, rigging equipment or temporary labor resources.

The judgments the individual makes about the values of these and other variables are important to the damage estimate. A different set of judgments can lead to an entirely different estimate of damages. It is preferable to estimate damages under the best (i.e., damage minimizing) conditions and the worst (i.e., damage maximizing) conditions, as well as the most likely conditions.

It is important to note that the analysts' best judgments are still clearly treated as the most likely outcome. However, there is now the capability to bracket that best guess with a high- and low-range estimate interval. This range of damages is based on the simple preservation of information readily available to Corps' analysts[25] about relationships, and values that are fundamentally uncertain. There was no esoteric mathematical or statistical computation required. Low estimates were cumulatively combined to produce the lower bound for damages; high estimates were cumulatively combined to produce the upper bound for damages. With a method such as this, no precise information is obtained about how damages might actually be distributed over the range created. Advanced statistical techniques can be used to address this problem in future research efforts. In the meantime, the creation of the range alone significantly improves the analysis. Lack of knowledge of the distribution of damages does not present a significant barrier to the analysis, as will be shown.[26]

Inundation Reduction Benefits

In this section, cumulative uncertainties become evident in the estimation of expected annual damages. Model and parameter uncertainty in the hydraulic and hydrologic (H&H) analyses, so critical to expected annual damage estimation, is well beyond the scope of this illustrative example. Nonetheless, expected annual damages cannot be discussed without addressing some of the risk and uncertainty inherent in the H&H analysis.

Single point estimates are commonly used to represent hydrologic and hydraulic relationships. For instance, a flow of 232,000 cfs may be defined as the 55-year flood event. In actuality, the analyst knows this relationship can never be defined with complete certainty. He or she may know the 232,000 cfs flow is somewhere between the 125-year and the 33-year event, with a recurrence interval of 55 years being the best estimate. This same flow may be estimated to produce a river stage of 545.5 ft., but the analyst knows that flows of different magnitudes have been measured at the same stage.

It is important to carry this knowledge through to subsequent analytical steps in the flood control project. The uncertainty in the frequency of the design flood translates into an uncertainty of expected annual damages, levels of protection and residual flood risk. Using the example here, the chance of the 232,000 cfs flood occurring one or more times during a 100-year project life is somewhere between 50 and 95 percent, with a best estimate of 84 percent. Uncertainty in the rating curve may affect the design and raising height of levees, floodwalls and other types of

---

[25] This point is worth reemphasizing. Risk and uncertainty analysis in the current context does not require the analyst to do extra work. It does require the analyst to preserve more of the information that is generated in an analysis. In this example, the analyst must use confidence intervals about the mean estimate and the knowledge that depth-percent damages vary from place-to-place and structure-to-structure. In the case of data gathered during interviews, it means recording the respondent's upper and lower estimate, as well as her most likely estimate.

[26] In the absence of better information, a triangular distribution can be specified. Its "parameters" are a minimum, most likely, and maximum value that the variable can take.

protection, as well as project economics.

Incorporating the uncertainty in project hydrology and hydraulics into other analyses provides a more complete picture of project costs and benefits than when this uncertainty is ignored. Information available to the analyst with no additional work and sound engineering judgment can be applied to characterize the uncertainty in the frequency and rating curves. This information can subsequently be incorporated into estimates of expected annual damages and project benefits.

Hydrology--The Frequency Curve

The frequency curve is typically constructed using historic streamflow records. The log-Pearson Type III distribution is used by Federal water resource agencies to translate the historic record of yearly peak flows into a flow-exceedence frequency curve. Sources of uncertainty surrounding the estimation of the frequency curve include data limitations, model specification,[27] and extrapolation of the frequency curve beyond observed flows to include large, extremely infrequent events.

Typically, the Corps' analyst relies on U.S. Geological Survey flow records and the HEC-1 program to develop the frequency curve. In practice, the analyst has little control over the quality or quantity of data or the uncertainty inherent in the HEC-1 model. Nonetheless, the analyst can use the estimated frequency curve and its confidence limits to quantify the risky nature of flooding.

Figure 7 shows the frequency curve for the Heck River at the study area. The confidence limits are the 67% confidence limits (plus and minus one standard error). What the confidence limits tell us is that if 100 frequency curves were developed for 100 different periods of record of the same length, 67 of the curves would lie within the confidence limits shown in the figure. In other words, the analyst is 67% sure that the 232,000 cfs event has an exceedence frequency per 100 years of between 0.8 and 3. An exceedence frequency of 1.8 per 100 years is the best estimate.

Table 11 shows a number of selected flood flows for the Heck River along with the low, expected, and high estimates of their exceedence frequencies. Lows are lower confidence limit values; highs are upper confidence limit values.

The analyst is warned about extrapolating the frequency curve and confidence limits much beyond the highest observed flow. The shape of the curve beyond this point is highly uncertain, and the confidence limits are expected to diverge more widely than shown in Figure 7. These events cause large damages, but since they are very infrequent, their contribution to the average annual damages is small in comparison to the more frequent events.

[27] There is substantial disagreement among the professional community about whether the log-Pearson III distribution is an appropriate choice for all flood frequency analyses.

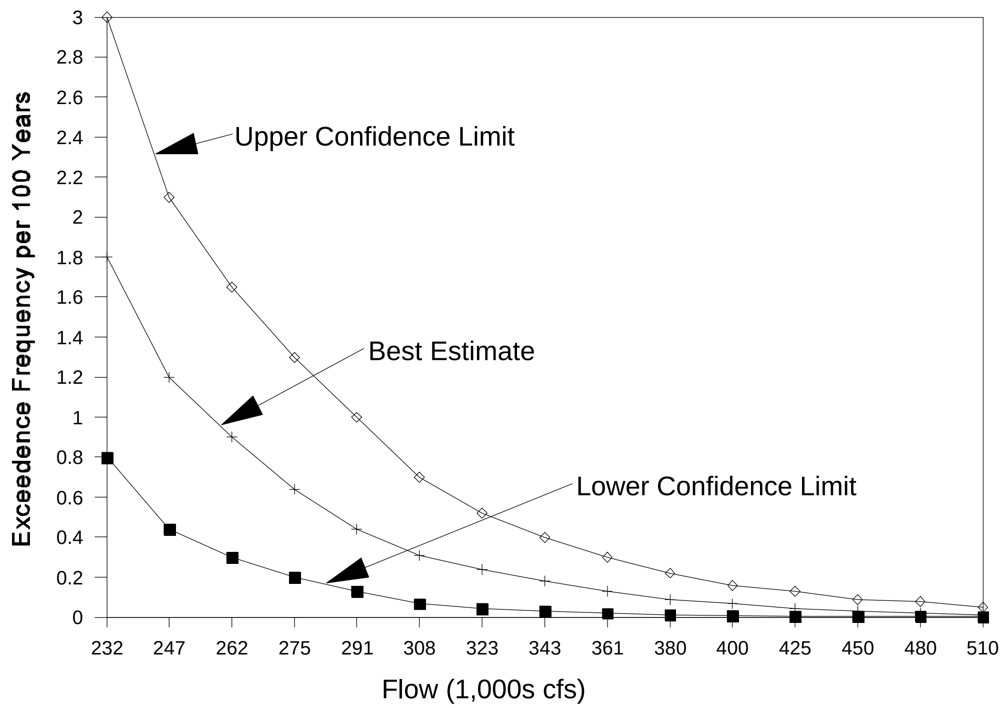


Figure 7: Heck Valley Frequency Curve

Hydraulics--The Rating Curve

Water surface elevations are calculated for various flows using the HEC-2 program. A rating curve relating stage to flow is then drawn. Typically, a single point estimate of stage for a given flow is presented. Though this gives a best estimate of stage and flow, the analyst knows there is some uncertainty in this relationship. Because the stage-flow relationship is used to design project features and to construct a damage-frequency curve to determine average annual flood damages, this uncertainty should be considered and quantified.

Some natural sources of uncertainty in the stage-flow relationship are the effect of wind and waves, debris, ice, the timing of rainfall and runoff, flow dynamics, etc. Major sources of uncertainty in the modeling and calculation of stage are the error in the selection of Manning's **n**, modeling of bridges and other flow obstructions, calibration to observed high water marks, modeling of channel cross sections, expansion/contraction factors for changes in channel width, and starting water surface profiles. The state of the art of hydraulic analysis is not yet able to handle all of the natural sources of uncertainty. Model uncertainty can be reduced by measures typically employed in Corps' analyses. For instance, in the Heck Valley study, the channel cross sections used in the HEC-2 analysis were physically surveyed to reduce the uncertainty associated with modeling channel dimensions. High water marks for large floods contained within the existing protection were also available. Uncertainty in Manning's **n** is addressed by adjusting **n** values to calibrate the model to within +/- 0.5 feet of observed high water marks.

Flow (1000 cfs)	Exceedence Frequency Per 100 Years		
	Low	Expected	High
232	0.800	1.800	3.000
247	0.440	1.200	2.100
262	0.300	0.900	1.800
275	0.200	0.640	1.300
291	0.130	0.440	1.000
308	0.068	0.310	0.700
323	0.044	0.240	0.520
343	0.030	0.180	0.400
361	0.020	0.130	0.300
380	0.012	0.090	0.220
400	0.009	0.068	0.160
425	0.007	0.044	0.130
450	0.006	0.030	0.090
480	0.005	0.200	0.080
510	0.004	0.012	0.050

Note: For flows beyond 400,000 cfs, lower confidence limits are not within the limits of the plotting paper. For sake of analysis, an estimated extrapolation is made.

Table 11: Frequency Ranges for Flows on the Heck River

Although the hydraulic model can be fine-tuned in this way, it is difficult and perhaps even futile to quantify the effect of model uncertainty on the stage-flow relationship. One may say that a moving volume of water that has been stated to be a 232,000 cfs flow will produce a stage between 545 and 546 feet, but what does this really tell us? It is known that a river stage of 545.5 feet has been accurately measured. The uncertainty lies with the fact that it is in reality unknown that the "model" flow of 232,000 cfs is, in fact, 232,000 cfs, because flow measurements themselves are inexact. Most published flow records are estimated to be within 10% of the actual flow. What can be stated, then, is at a stage of 545.5 feet MSL, the expected flow is 232,000 cfs. Low and high boundaries on this flow can be estimated, so it can be stated, for example, that the actual flow at 545.5 MSL is somewhere between 209,000 and 255,000 cfs, i.e., 232,000 cfs ±

13,000 cfs. Table 12 presents the estimated range of flows that could attain a given elevation under various sets of circumstances.

What can readily and reasonably be quantified, is the range within which some uncertain flow has occurred, producing a measured stage. Together with the frequency curve, this gives a range of how frequently this stage can be expected to occur.

There are many more sophisticated risk and uncertainty issues in a detailed hydrologic and hydraulic analysis. These, however, are beyond the scope of this example.

<u>Hydrology, Hydraulics, and the Stage-Frequency Relationship</u>

The above-described uncertainty in the hydrology and hydraulics of flood events can be incorporated into the expected annual damage calculations for the Heck Valley. Since damages are calculated for increments of stage, what is desired to know is how frequently the river will reach a particular stage, or more appropriately, what is the highest, the expected, and the lowest frequency with which the previously used river stage of 545.5 will be seen. Two components of this frequency are the range in flows expected for a given stage and the range in frequency for the low, expected, and high flows defining that range. Table 13 shows how this can be represented using an assumed ±10% accuracy of the flow records and the 67% confidence limits about the frequency curve (Figure 7). For a stage of 545.5 MSL, the expected exceedence frequency per 100 years is 1.8 for the expected flow of 232,000 cfs. But this stage may have an exceedence frequency per 100 years as high as 5.2, found from the higher confidence limit for the 209,000 cfs event. Similarly, the lowest exceedence frequency is associated with the high flow of 255,000 cfs, found to be 0.34 as taken from the lower confidence limit of this event.

Elevation in Feet Above MSL	Flow in 1000 cfs	
	Minimum	Maximum
534	125	125
535	128	135
536	135	146
537	140	153
538	146	161
539	152	170
540	160	180
541	167	192
542	174	205
543	183	215
544	195	230
545	203	248
546	215	255
547	227	265
548	238	280
549	250	295
550	266	309
551	280	338
552	293	355
553	311	376
554	325	402
555	344	432
556	361	448
557	380	475
558	400	500

Table 12: Rating Curve

This development of the stage-frequency relationship uses information and engineering judgment that is readily available to define the flood event. It is a more realistic representation of the event than single point estimates of hydrologic and hydraulic relationships. The information in

Elevation in Feet Above MSL	Flow (1000 cfs)			Exceedence Probability/100 Yrs.		
	Low	Expected	High	Low	Expected	High
545.5	209	232	255	5.200	1.800	0.340
546.5	222	247	272	4.000	1.200	0.210
547.5	236	262	288	3.000	0.900	0.130
548.5	248	275	303	2.200	0.640	0.090
549.5	262	291	320	1.800	0.440	0.054
550.0	277	308	339	1.300	0.310	0.032
551.5	291	323	355	0.950	0.240	0.022
552.5	309	343	377	0.700	0.180	0.013
553.5	325	361	397	0.550	0.130	0.009
554.5	342	380	418	0.400	0.090	0.007
555.5	360	400	440	0.300	0.068	0.006
556.5	383	425	468	0.220	0.044	0.005
557.5	405	450	495	0.160	0.030	0.004
558.5	432	480	528	0.120	0.020	0.003
559.5	459	510	561	0.080	0.012	0.002

Table 13: Frequency Ranges for Stages on the Heck River

Table 13 is appropriate for use in the calculation of expected annual damages.

Expected Annual Damages

Preceding sections have described substantial uncertainty in the estimation of the relationships that comprise the hydro-economic model used to estimate expected annual damages. The stage-damage relationship (damage curve), the stage-flow relationship (rating curve) and the flow-frequency relationship (frequency curve) are replete with natural, theoretical, model, and parameter uncertainty.

The cumulative effects of the various sources of uncertainty were accounted for in the estimation of the expected annual damages.[28] Expected annual damages were estimated using a spreadsheet program written for Lotus 1-2-3. Values in the spreadsheet cells were varied, consistent with the above descriptions, using @RISK, a Lotus add-in program.

[28] The numerical examples in this and the following section are based on protection from a flow of 290,000 cfs. This is the two-foot levee raising.

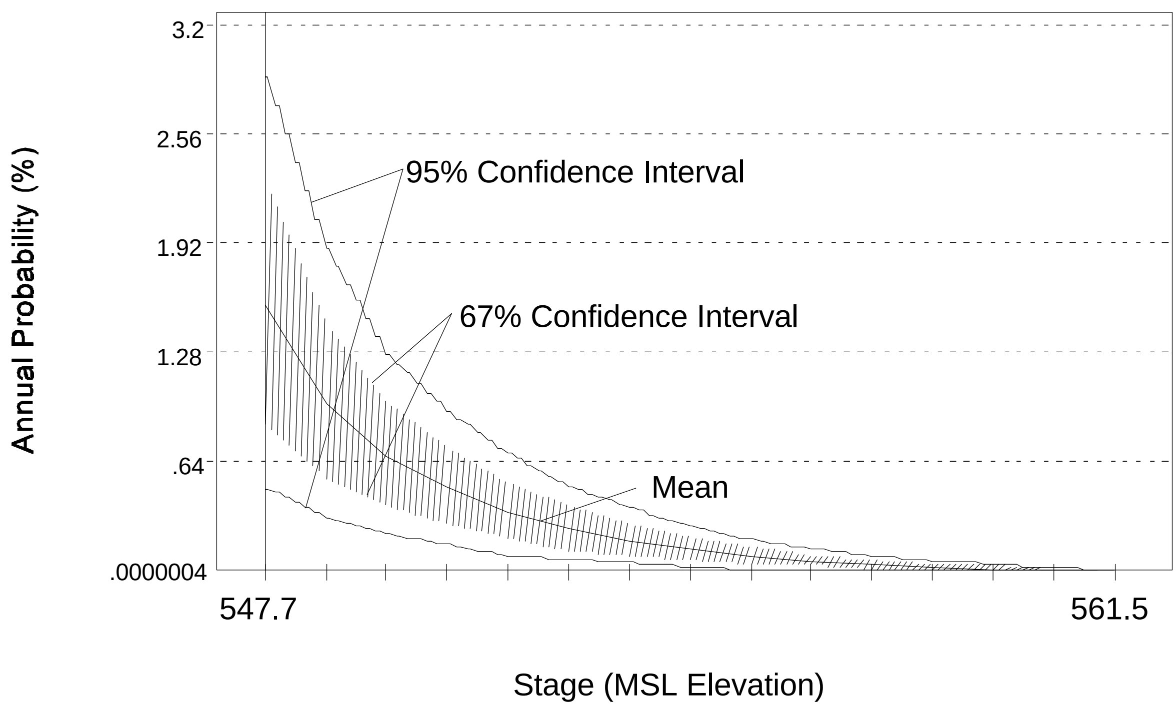


Figure 8: Stage Frequency Curve Distribution

Damages at each stage were permitted to vary over an assumed range of normally distributed damages. The frequency with which a given stage would be obtained was permitted to vary over an assumed triangular distribution of flows. The stage-frequency distributions were generated by combining the uncertainty in the rating and frequency curves, as described above. The minimum, maximum, and most likely flows estimated reflect the most frequent occurrence of the minimum flow, the least frequent occurrence of the maximum flow and the traditional best estimate of the stage-frequency at each given stage. Each relationship was modeled independently and was simultaneously allowed to vary during a 10,000- iteration simulation of the model.

Freeboard performance of the existing and improved projects was also stochastically modeled in the analysis (Freeboard will be addressed specifically in a subsequent section). A simulation model using Lotus 1-2-3 and @RISK was built to incorporate all the above factors. The model logic precluded the possibility of anything other than monotonic relationships. There was one model for the without-project condition and one for the with-project condition. The without- and with-project computations used the same basic H&H and damage data. Only those parts of the relationship actually affected by the plan varied. Each iteration used internally consistent logic, but each iteration was independent.

Figure 8 presents the stage-frequency curve generated from a 10,000-iteration simulation in which the stage-flow and flow-frequency curves' uncertainty have been combined. This figure shows that, at any given elevation, there is a range of probabilities (exceedence frequencies can be directly obtained from the number of events per 100 years) that floodwaters will reach any height. That range can be explained by the uncertainty inherent in the hydrology and hydraulics described

9a: Frequency at 548.7 MSL

9b: Frequency at 553.5 MSL

9c: Frequency at 559.5 MSL

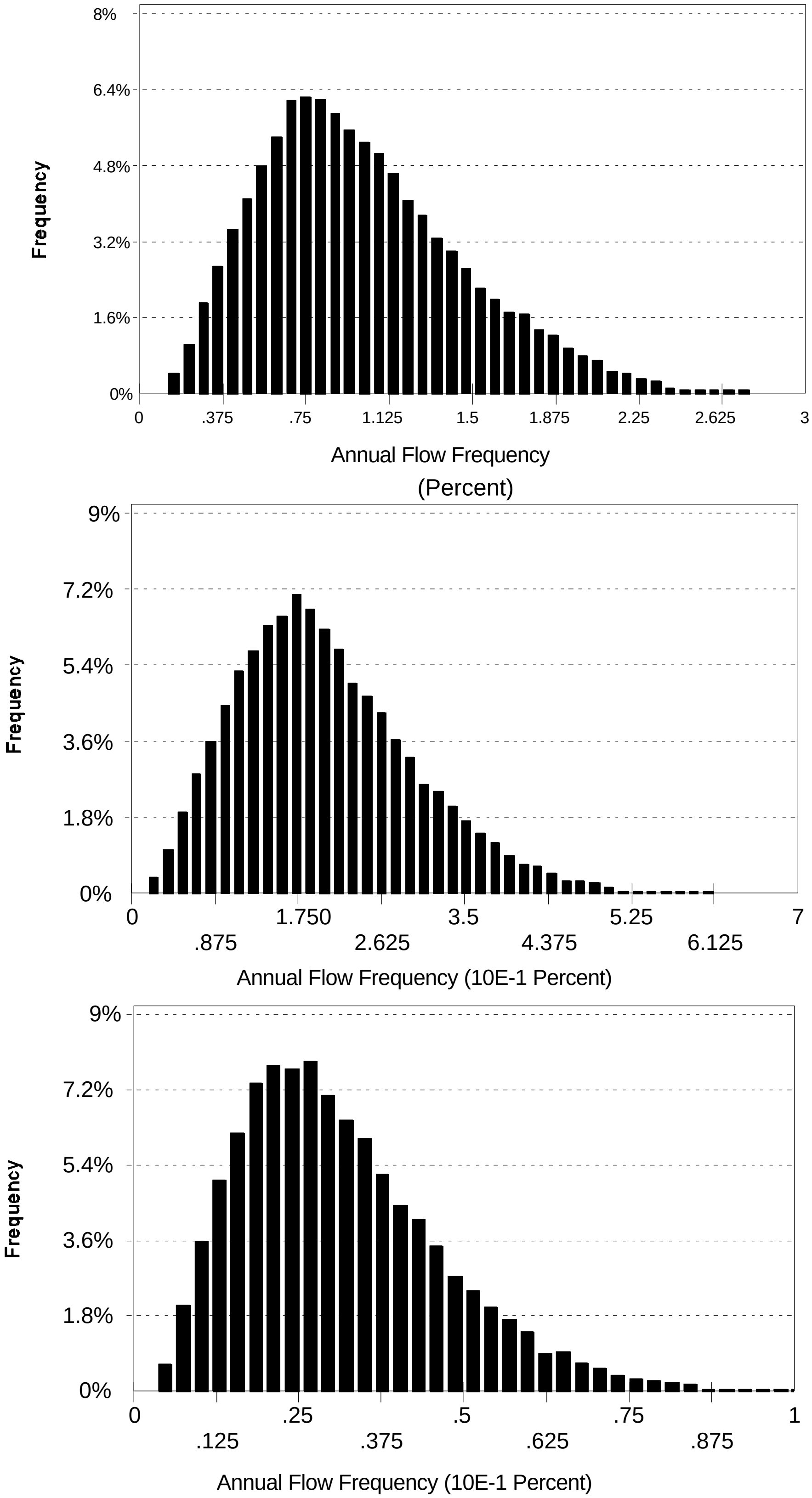


Figure 9: Flow Frequency Distributions

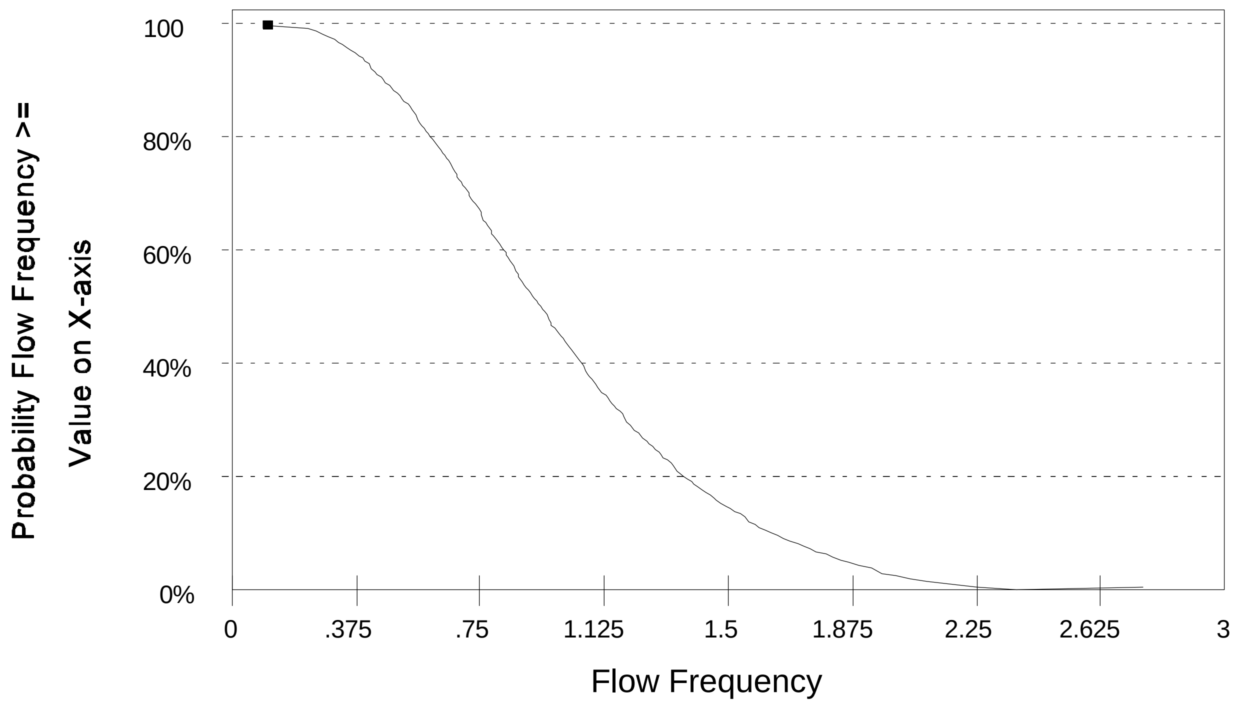


Figure 10: Flow Frequency at 548.7 MSL Cumulative Distribution

above. Traditional analysis would be based on a single stage-frequency curve. The analysis shown here recognizes that the true stage-frequency relationship could lie anywhere in the interval shown.

Figure 8 is, in reality, a three-dimensional relationship. Figure 9
, parts (a) through (c), shows the distribution of events per 100 years at 548.7, 553.5, and 559.5 MSL. At each elevation, there is a distribution of the number of events per 100 years at that elevation. The mean of this distribution is, in the absence of information to the contrary, the best estimate of the true value. The mean of each distribution becomes, in essence, a point on what is analogous to the traditional stage-frequency curve. Figure 10 presents the information contained in Figure 9(a) in the form of a cumulative distribution function.

The stage-damage curve generated in the 10,000-iteration simulation is presented in Figure 11. It, too, is three-dimensional. Figure 12a) shows the damage histogram at 548.7 MSL. There is about an 80 percent chance that no damage will occur at this stage because most flows that attain this height are contained by the freeboard.[29] Flows that do escape the existing levee cause damages in the range of about $450 to 600 million. Figures 12(b) and (c) show the distribution of damages at higher elevations.

---

[29] This is an assumption imposed by the analyst. Freeboard is discussed in detail in a subsequent section.

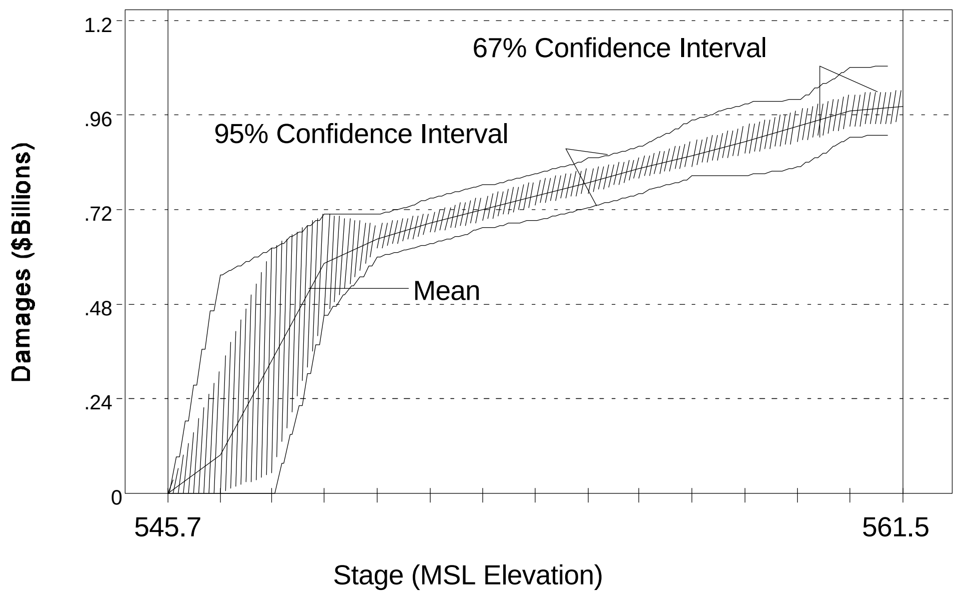


Figure 11: Stage Damage Curve Distribution

Figures 13 and 14 show the frequency histograms of without- and with-project expected annual damages. These are obtained from the combination and integration of curves randomly generated from Figures 9 and 11. The benefits generated by subtracting with-project expected annual damages from without- project damages for each iteration are shown in Table 14. This table summarizes the essence of the rationale for risk and uncertainty analysis succinctly.

In the Corps' planning process, analysts are asked, "What is the benefit of building this project?" Corps' studies have been estimating benefits for decades. Table 14 represents a peak behind the pages of these reports to reveal the fuller truth. To the question, "What are the benefits of this project?", the only honest answer is, "We don't know." In the case of Heck Valley, the benefits are expected to be $2,843,000 annually. The truth is that benefits could be as low as $0 or as much as $14,580,000 annually.[30]

[30] The simulation results presented represent a significant step forward in the economic analysis of projects. If the simulation model is well-constructed, the results will generally be better the larger the number of iterations. Simulations allow opportunities for substantial sensitivity analyses as well. For example, the parameters of the normal distributions, assumed to describe damages, could be varied. The assumed distribution itself could be varied from, say, a normal distribution to a triangular, Weibull, or even exponential distribution. If all other relationships in the model are constant, the difference in results is clearly attributable to the assumed distribution of damages. Likewise, all the assumptions of the model could be systematically varied. The model presented in the text is an improvement over traditional analysis, but substantial improvements can be made to the presented

How can there be such a range in results? If the existing project performs[31] better than it is expected, and the new project worse than is expected, benefits will be low. For example, if without-project damages are actually much lower than expected, for reasons detailed earlier; and if the stage reached by a certain flow is much less than expected; and if the frequency of this flow is less than expected; and if freeboard functions better than expected in the existing project; then, expected annual damages may be very low. In this 10,000- iteration simulation, the lowest estimate obtained was $755,000. If the same basic relationships hold with the project and perhaps the new freeboard does not function as well, then expected annual damages may not be reduced much at all by the new project. Although highly unlikely, it is possible that the project would produce no benefits at all.

On the other hand, if the existing project does not perform as well as expected and the new project performs even better than expected, benefits could be very high. For example, if damages are greater than expected; and if the stage reached by a particular flow is greater than expected; and the frequency of that flow is in reality higher than expected; then, expected annual damages could be much greater without the project. If the project performs better than expected, with-project expected annual damages may be very low. The result--much higher-than-expected benefits.

While the mean of a distribution of simulated expected annual damages cannot *a priori* be expected to equal the "traditional" single estimate of expected annual damages, it is in every respect comparable to that traditional estimate. This type of analysis does not weaken the analyst's ability to say, "The best estimate of benefits is ...." That can still clearly be done. In this case, the best estimate is $2,843,000. Now the analyst can go even further and provide the decision-maker with information that was never available before.

If the best estimate of benefits is low, decision-makers can look at the range of possible outcomes and give weight to the honest possibility that actual benefits from this project could be more than five times greater than estimated. The Corps' old saw of "benefits are <u>conservatively</u> estimated to be..." can now be interpreted in a new light by decision-makers, if so desired. The answer to the question, "What would benefits be if they weren't so conservatively estimated?", is now before the analyst and decision-maker.

---

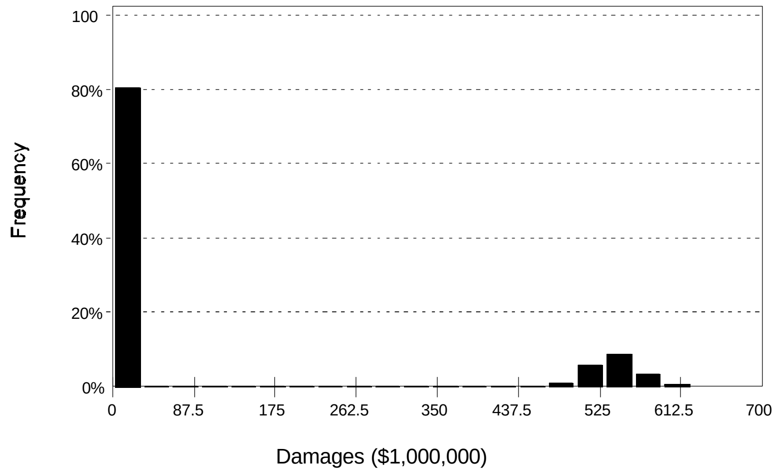
analysis as well.

Another possibility to improve the analysis would to be to develop a distribution of simulation results. For example, if we seek the best possible estimate of benefits, the analyst could conduct several hundred simulations (of thousands of iterations each) to generate hundreds of estimates of the mean benefits from the simulations. These mean benefits would themselves have a distribution.

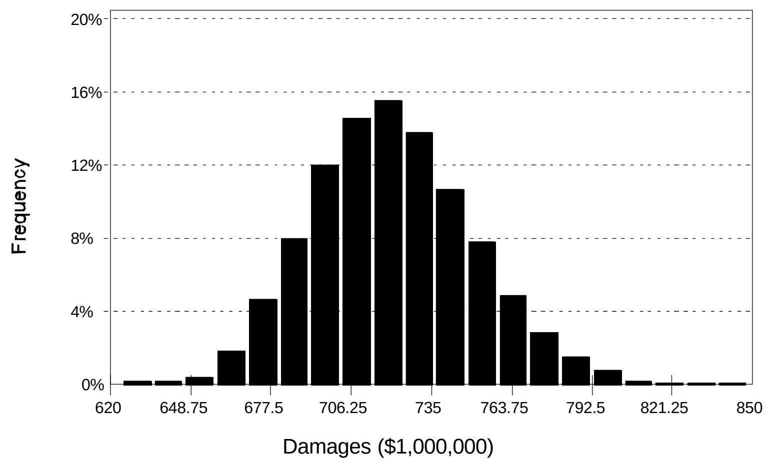
The idea is not to find ways to increase the analytical demands on Corps' planners. Instead, it is to find out what is most important to economic feasibility, plan formulation, etc., and to analyze it thoroughly,
preserving information along the way for use in the decision process.

[31] In this context, performance is measured by expected annual damages.

12a: Frequency
at 548.7 MSL



12b: Frequency
at 553.5 MSL



12c: Frequency
at 559.5 MSL

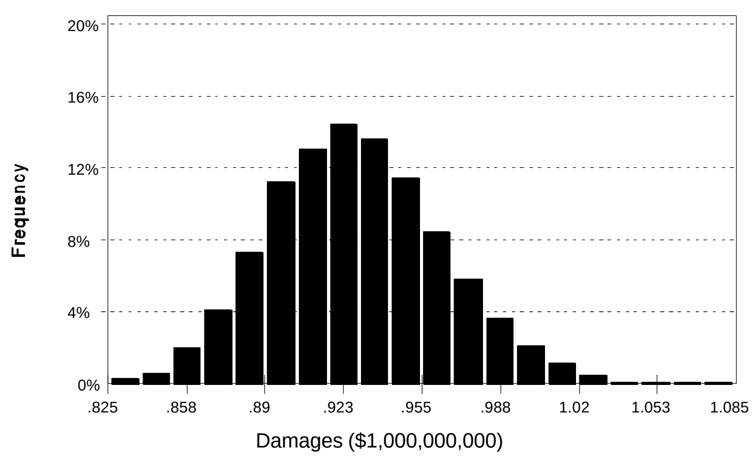


Figure 12: Damages at Various MSL Frequency Distributions

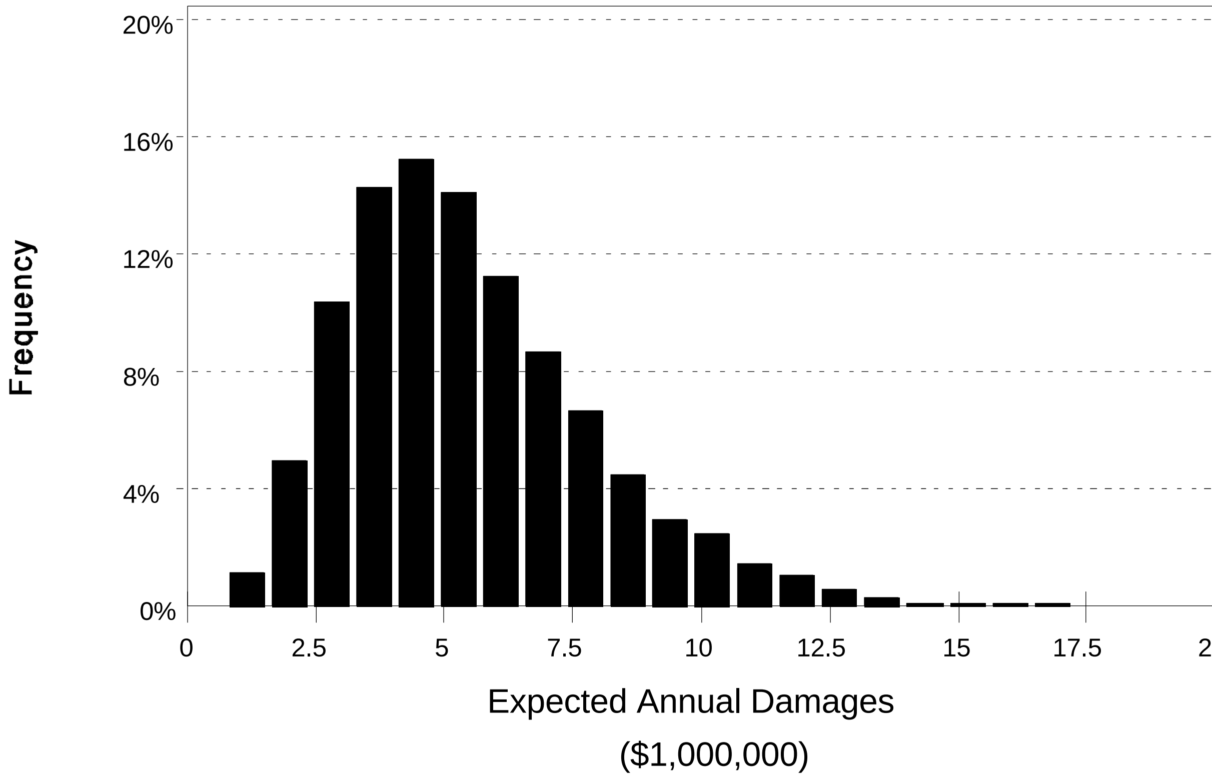


Figure 13: Without Project EAD Frequency Distribution

Figure 15 presents the cumulative distribution of the simulation results for benefit estimates. With these functions, the probability that any value greater than that shown on the horizontal axis will be realized can be read from the vertical axis. For example, the probability of benefits greater than $1.5 million is 0.65, greater than $3 million is 0.39, greater than $4.5 million is 0.21, greater than $6 million is 0.11, greater than $7.5 million is 0.06 and greater than $9 million is 0.02.

Project Costs

Costs are another source of uncertainty with tremendous implications for plan formulation and project feasibility. Table 15 presents an extract from a typical cost estimation table for the Tonsking project.

Costs are typically estimated on the basis of quantity estimates and unit costs or lump sum cost estimates for other project elements. Contingencies of 20 percent are routinely built into cost estimates in recognition of the uncertainty inherent in the estimation of project costs. Project costs can vary because of changes in the project design due to unanticipated circumstances, errors in quantity estimates, changes in prices and a variety of other factors.

The cost estimate of Table 15 could readily be revised to allow analysts to build their

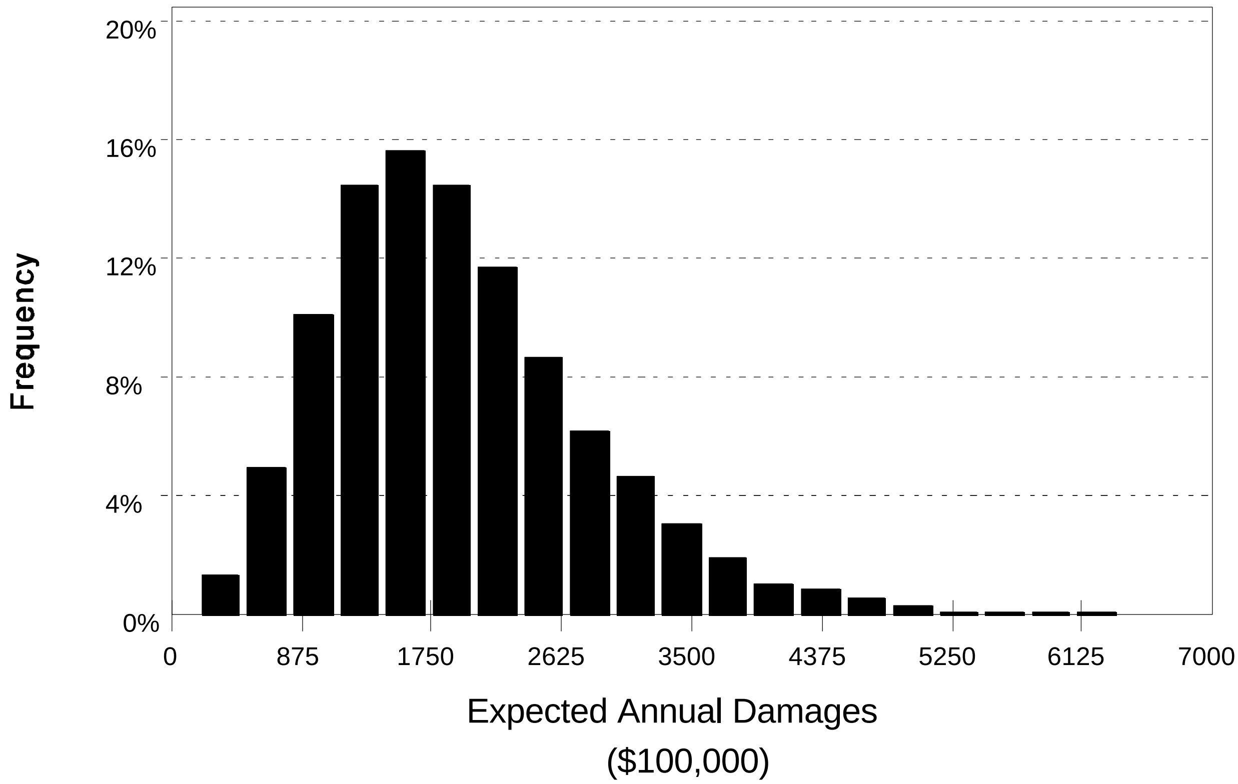


Figure 14: With Project EAD Frequency Distribution

uncertainty into their estimates. Analysts could let their quantity estimates vary over a range of values when they were not exactly sure of the quantity required. For example, the expected amount of land acquired for the project is 26 acres. In fact, some of the needed land may already have been purchased for the existing project, planimeter estimates of the land needed may be inaccurate, or land ownership may require the purchase of entire parcels now in private ownership where only part of the parcel is needed for the project. Some land may be donated for the project, or easements could be obtained for other land.

In recognition of this uncertainty, acreage requirements are allowed to range from a minimum of 20 to a maximum of 35 acres, with a most likely requirement of 23 acres.[32] It is

[32] The acreage requirements are assumed to have a triangular distribution with minimum, most likely and maximum values as specified. The triangular distribution is useful when the exact distribution of the data is not known. Other distributions may be more appropriate. The distributions used in this case study were chosen primarily for their expediency.

The 26 acres seen in the cost table is the expected value of a triangular distribution, with the parameters shown in the text. Thus, triangular distributions do not always yield expected values equal to the best estimate of the planner.

	Pre-Project EAD	Post-Project EAD	Project Benefits
Mean	$ 5,501	$ 2,658	$ 2,843
Minimum	755	297	0
Maximum	16,924	8,154	14,580
Range	16,168	7,857	14,580
Standard Deviation	2,479	1,056	2,417

Table 14: Expected Annual Damage and Benefit Distributions ($1000's)

useful to note that the analyst's estimate of 23 acres of land being required is still looked upon as

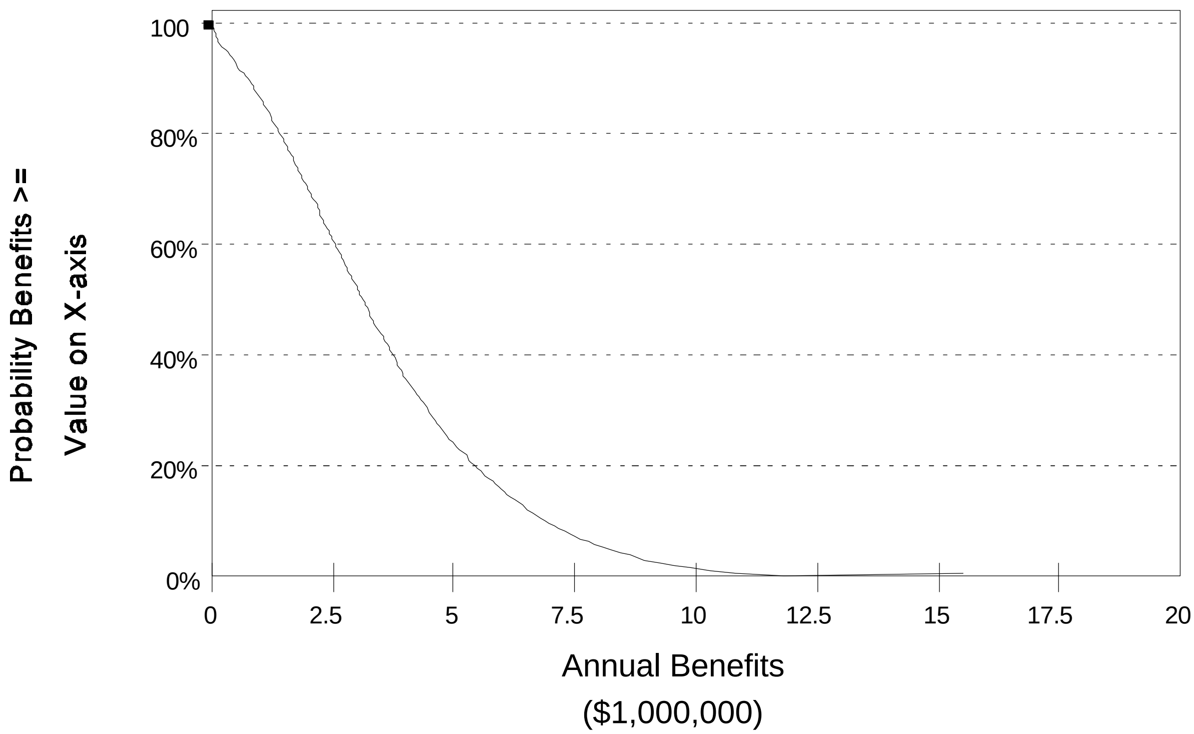


Figure 15: Benefits Cumulative Distribution

the most likely land need. In this respect, no additional work is created for the analyst. The analyst is also allowed to introduce additional information into his estimate by specifying the minimum and maximum land needs for this project.

Likewise, unit costs of land are also allowed to vary, according to a triangular distribution, from $12,000 to $20,000 per acre, with the most likely cost being $15,609.[33] Land costs are likely to be most sensitive to zoning and impact on contiguous lands.

The calculations shown in Table 15 were incorporated into a spreadsheet risk model, and Latin Hypercube[34] simulation procedures were applied using @RISK. In combination, quantities are allowed to vary while unit costs vary independently with respect to the quantities.[35] This can be done for every cost item in the estimate. Using @RISK, the majority of all quantities, unit costs, lump sum estimated costs, contingency rates, and E&D, S&A costs are allowed to vary independently of each other. Distributions used to model these varying values include triangular, discrete, cumulative, normal, lognormal, uniform, general and histogram.

[33] This value also deviates from the expected value shown in the cost table for the same reason described in the previous footnote.

[34] Latin Hypercube simulations are more efficient than a Monte Carlo simulation, though the principles of each are similar. Where a Monte Carlo simulation selects iteration values from the cumulative distribution at random, Latin Hypercube simulations, in effect, divide the cumulative distribution into equal width cells and samples a random value from each cell.

[35] It would be perfectly feasible to incorporate dependence of quantities and unit costs to account for such things as quantity discounts, economies of scale, increasing marginal costs, etc. Because much of this case study is hypothetical, little emphasis has been given to modelling dependent relationships.

DESCRIPTION	UNIT	ESTIMATED QUANTITY	UNIT COST ($)	ESTIMATED COST ($)
01. LANDS & DAMAGES				
Lands	JOB	26	15,869.67	412,611
Acquisition Costs	JOB	--	LS	14,800
Net Land and Damages Cost				370,000
Contingencies (16%)				55,500
TOTAL LAND AND DAMAGES COSTS				**$425,000**
02. RELOCATIONS				
Relocate W St. Sanitary Diversion Chamber	JOB	--	LS	23,333
Lengthen Water Tunnel at Sta. 111+35 and 101+50	JOB	--	LS	36,333
Extend 36" Sanitary Force Main through I-Wall at Sta. 28+50	JOB	--	LS	16,333
Remove 30" Storm Sewer from Sta. 150+20 and Replace Riverward	JOB	--	LS	62,333
Net Relocation Cost				137,000
Contingencies (16%)				20,550
SUBTOTAL				157,550
Engineering and Design (15%)				23,633
Supervision and Inspection (5%)				7,878
TOTAL RELOCATIONS COST				**$189,060**
11. LEVEES AND FLOODWALLS				
Care and Protection of Levee	JOB	--	LS	20,000
Temporary Access Roads	JOB	--	LS	16,667
Remove Grouted Riprap & Floodwall	JOB	--	LS	18,367
Remove RR Closure @ Sta. 150+80	JOB	--	LS	39,000
Remove & Replace 6'Chain Link Fence	LF	1,600	14.10	21,600
Remove & Replace Bit. Pave.	SY	960	19.00	18,240
Nature Park Access Road	JOB	--	LS	116,667
K St. Park Access Road	JOB	--	LS	35,000
L Ave. Pump Sta. Access Road	JOB	--	LS	19,000
Ramp P St. over Levee	JOB	--	LS	6,250
Clearing and Grubbing	AC	7	3,500.00	25,200
Stripping	CY	95,000	4.65	456,000

Table 15: Construction Costs Estimates - Heck Valley Flood Protection

DESCRIPTION	UNIT	ESTIMATED QUANTITY	UNIT COST ($)	ESTIMATED COST ($)
Common Excavation	CY	71,677	5.38	396,000
Structural Excavation	CY	16,000	16.00	240,000
Impervious Fill	CY	543,333	1.70	816,000
Impervious Burrow	CY	569,667	7.20	4,240,800
Random Fill	CY	21,500	1.60	35,200
Unconfined Impervious Backfill	CY	1,950	5.88	10,450
Structural Backfill	CY	11,133	9.08	105,450
Drainage Fill (Floodwall)	CY	1,500	25.50	51,000
Drainage Fill (Levee)	CY	45,000	25.00	1,102,500
Bedding Material	CY	1,750	27.00	46,750
Remove,Stockpile & Replace 12"Riprap	CY	1,000	33.00	33,000
12" Riprap	CY	2,353	60.00	147,600
12" Grouted Riprap	CY	100	140.00	14,000
Topsoil	CY	48,300	7.00	350,175
Seeding and Mulching	AC	68	1,800.00	163,200
Concrete (I-Wall)	CY	415	245.00	102,500
Concrete (T-Wall)	CY	5,215	330.00	1,590,575
Waterstops	LF	1,550	6.00	10,296
Reinforcing Steel	LB	420,000	0.73	252,000
Sheetpiling (PZ-27)	SF	4,890	22.00	109,340
Sheetpiling (PZ-38)	SF	9,413	25.00	236,000
Miscellaneous Metal	LB	6,400	2.20	14,080
Welding Sheetpiling Joints	LF	490	45.25	22,050
Windy Storm Pump Sta. Flood Protec.	JOB	--	LS	2,660,000
Seepage Cutoff Walls:				
Heck Valley Expressway	JOB	--	LS	237,000
C St. Sanitary Pump Station	JOB	--	LS	294,000
L Ave. Sanitary Pump Station	JOB	--	LS	274,000
Relief Well Systems:				
C St. Storm Pump Station	JOB	--	LS	202,000
L Ave. Storm Pump Station	JOB	--	LS	127,000
Relief Wells (49 Ground Discharge)	LS	1,725	375.00	634,550
Relief Wells (85 Collector Discharge)	LF	3,100	370.00	1,174,750
Pumping Tests	EA	134	308.33	40,870
Splash Pads	EA	134	257.50	33,500

Table 15 (cont.): Construction Costs Estimates - Heck Valley Flood Protection

DESCRIPTION	UNIT	ESTIMATED QUANTITY	UNIT COST ($)	ESTIMATED COST ($)
Grout Existing Wells & Collector Pipes	CY	178	90.00	16,200
12" Perforated Collector BCCMP	LF	1,500	16.50	23,100
36" Collector BCCMP from Sta. 124+00 to 100+00, 12+00 to 42+00, and 101+00 to 126+00	LF	8,200	105.00	861,000
Collector Pipe MHs	EA	20	1,750	35,000
Closure Structures:				
P St. Bridge	JOB	--	LS	600,000
M St. Bridge	JOB	--	LS	1,050,000
X St. RR at Sta. 100+80	JOB	--	LS	197,000
W Ave.	JOB	--	LS	460,000
Conrail at Sta. 150+00	JOB	--	LS	222,500
Drainage Structures and Pump Station Appurtenances:				
Heck Valley Expressway (1/2-Circle Pipe Spillways replace with 24" CPM)	JOB	--	LS	32,600
Sta. 147+50 (Extend 36" CPM Outlet)	JOB	--	LS	5,400
C St. Relief Culvert (Extend Inlet)	JOB	--	LS	86,000
K St. Park Relief Culvert (Raise Inlet Walls)	JOB	--	LS	11,700
L Ave. Storm Pump Station (Extend Discharge Line Through I-Wall)	JOB	--	LS	5,500
W St. Relief Culvert (Increase Capacity by 50%)	JOB	--	LS	330,000
Teddy Cr. Culvert (Increase Capacity by 50%)	JOB	--	LS	440,000
Extend W St. Relief Culvert (Inlet, Relocate Pump Sta., Inlet Chan, & Control Weir)	JOB	--	LS	110,000
Net Levee & Floodwall Cost				20,803,776
Contingencies (15%)				3,120,566
SUBTOTAL				23,924,342
Engineering and Design (14%)				3,349,408
Supervision and Inspection (5%)				1,196,217
TOTAL LEVEE & FLOODWALL COST				**$28,469,967**

Table 15 (cont.): Construction Costs Estimates - Heck Valley Flood Protection

DESCRIPTION	UNIT	ESTIMATED QUANTITY	UNIT COST ($)	ESTIMATED COST ($)
14. RECREATIONAL FEATURES				
Bituminous Bicycle/Jogging Path (16,300 LF0)	JOB	--	LS	145,000
Net Recreational Features Cost				145,000
Contingencies (20%)				29,000
SUBTOTAL				174,000
Engineering and Design (18%)				31,320
Supervision and Inspection (%5)				8,700
TOTAL REC. FEATURES COST				**$214,020**
COST SUMMARY - HECK VALLEY FLOOD PROTECTION PROJECT				
LANDS AND DAMAGES				$425,500
RELOCATION				189,060
LEVEES AND FLOODWALLS				28,469,967
RECREATIONAL FEATURES				214,020
TOTAL PROJECT COST				$29,298,547

Table 15 (cont.): Construction Costs Estimates - Heck Valley Flood Protection

Under traditional Corps' approaches, project first costs for the Tonsking project would be estimated as $29,295,000. This single number reporting implies a level of certainty that simply does not exist. Allowing quantities and costs to take random values consistent with their assumed distributions, 4,000 cost estimates were generated. Table 16 presents summary statistics for this distribution. Costs ranged from a low of $27.5 million to a high of $32.0 million. The expected cost of the Tonsking project obtained from this 4,000- estimate sample is $29,766,000.[36] This means costs will most likely be about $29.8 million, and this is the single value that would be used to represent costs, rather than the $29.3 million single estimate noted above.

Figure 16 presents a frequency histogram for the cost estimates summarized in the table. Figure 17 presents a cumulative distribution of cost estimates. A distribution such as this can be used to make confidence statements about the cost estimates. For example, there is a 65 percent chance that the project will cost $30 million or less; a 22 percent chance it will cost $29.295 million (traditional project costs) or less; a 0.18 percent chance the project will cost less than $28 million; and a 0.0003 percent chance it will cost $27 million or less. Using this information, it can

[36] In establishing distributions for the quantities and costs in this case study, the authors chose values that tended to reflect the view that cost estimates generally turn out to be lower than actual costs, i.e., the distributions were generally defined with a skew that increased costs. There is no reason why cost estimates could not be lower than costs estimated in the traditional way, particularly if the analysts traditionally tend to try to overestimate costs and quantities in their best estimates.

be stated that the probability costs will be between $29.295 and $30 million is 0.43 (0.65 - 0.22). Information like this can aid decision-makers who must decide if they are willing to bear the risk of cost increases, etc. Such information becomes even more useful in light of the Water Resources Development Act of 1986's imposed limitations on project cost overruns.

Contingencies can be viewed in a number of ways in this setting. If the distributions of quantities and costs are comprehensive, contingencies can be eliminated; they are built into the distributions. If contingencies are included for other reasons, or if the distributions are based on certain assumptions about foundation conditions, etc., contingencies can be included as a fixed percentage or as a random variable with a distribution.

Sample Size	- - - - - 4,000
Average	- - 29,766,500
Median	- - 29,776,300
Mode	- - 29,606,700
Variance	- - - - - 4E+11
Standard Deviation	- - - - 608,040
Minimum	- - 27,810,300
Maximum	- - 31,581,600

Table 16: Descriptive Statistics

Figure 16: Construction Costs Frequency Distribution

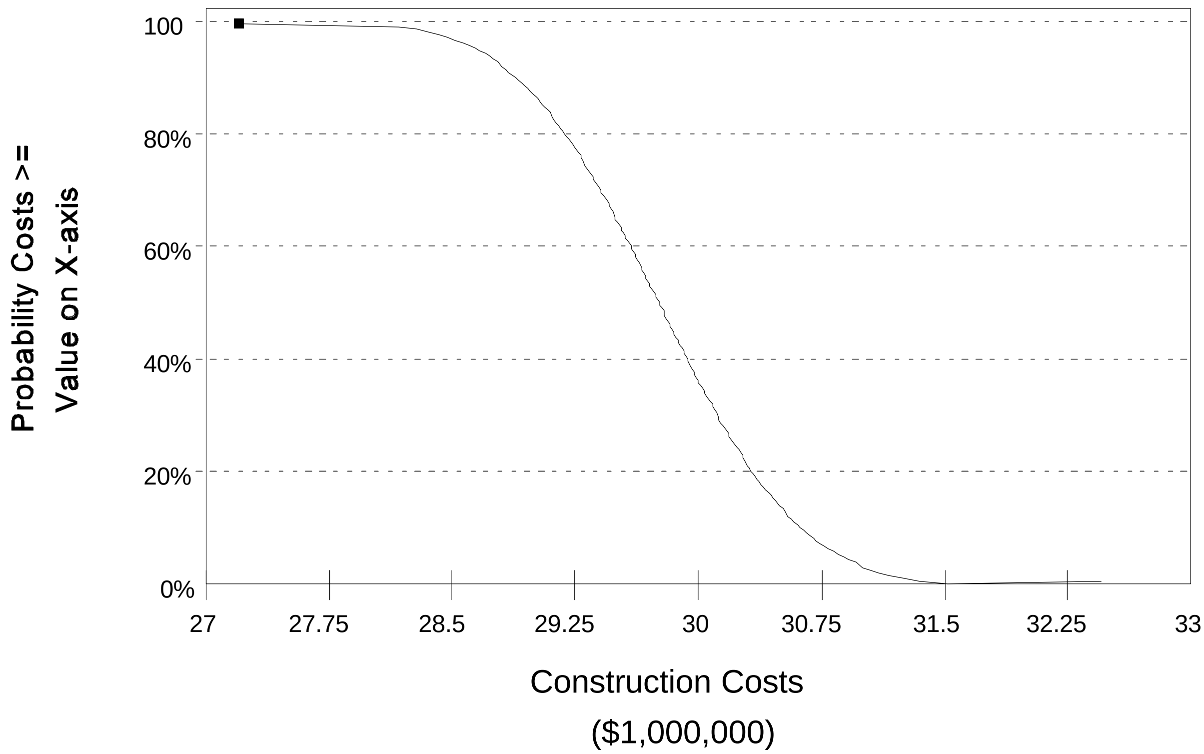


Figure 17: Construction Costs Cumulative Distribution

Statistical tests[37] determined that project costs are normally distributed with a mean of $29.8 million and a standard deviation of $608,040. This remarkably concise description of project costs can be used to make estimates of the probability of any particular cost being incurred using a standard normal distribution table.

Summary

The estimation of project benefits and costs for the Heck Valley community of Tonsking has demonstrated several things. First, it has shown how the cumulative effects of uncertainty in various tasks in a flood control study can be brought together and addressed in a reasonably coherent manner. More importantly, this analysis identifies ways to reduce uncertainty. This was done primarily by preserving information and openly admitting the limits of our knowledge.

The economist did not have to choose a single best estimate of average structure and contents value. The hydrologist did not have to desert the information stored in the flow record. The hydraulics engineer was allowed to admit the analysis was not precise to the inch. The cost

[37] Both the Kolmogorov-Smirnov and chi-square tests indicate the data are normally distributed.

estimator could acknowledge that the amount of land that would have to be acquired was not known, and would not be, until title searches and field surveys were complete. No one was forced to chose one number from among many. No new work was required to identify these limits to our knowledge. When it was all done, there was a best estimate of damages without and with the project, of benefits and of costs to report, but this time there was even more information available.

COMPARISON OF ALTERNATIVE PLANS

The initial comparison of plans is invariably made on the basis of economic performance, as summarized by the benefit-cost ratio. This section begins with a discussion of the benefit-cost ratio and returns to take up several of the formulation issues raised earlier.

BENEFIT-COST RATIO

It has been argued in previous sections that there is no single estimate of benefits and no single estimate of costs. In fact, it has been argued that these are random variables and that there is a distribution of each. If expected annual benefits can take many values and expected annual costs do likewise, it stands to reason the ratio of these two numbers can take many different values.

The simulation model described above estimated expected annual damages without and with the project. These were the sources of benefit estimates for the project. During each iteration of the simulation, a cost estimate was also randomly generated from the distribution of first costs previously described. Annual costs of construction were estimated straightforwardly from these estimates.

The increase in operation and maintenance costs, not previously discussed, was assumed to average about 0.1 percent of project costs. However, the actual percentage increase was assumed to be normally distributed, with a mean of 0.1 and a standard deviation of 0.05. Total annual costs are comprised of interest and amortization on the first costs and increased O&M costs. Interest during construction has been ignored in the analysis to simplify the presentation.

Each iteration of the simulation generated a random estimate of benefits and costs based on the distributions in the expected annual damage simulation spreadsheet. From these values, net benefits and the benefit-cost ratio (BCR) were generated. Figures 18 and 19 show the frequency histograms for net benefits and the BCR for the 290,000 cfs plan. Figures 20 and 21 show the cumulative distributions.

The BCR is not a known constant value, but is rather a random variable. Its value depends on all the things that determine benefit estimates (this case study is restricted to inundation reduction estimates) and all the things that determine cost estimates. The BCR has a distribution of values. Some values are more likely than other values. This is a critically important piece of information to convey to decision-makers. The distribution of BCR's for the Heck Valley project is summarized in Table 17.

The expected BCR is 1.38, indicating an economically feasible project. The BCR distribution is a truncated normal distribution (negative values are illogical). It appears, in the figures, to have a roughly exponential distribution; it does not. Low values are more likely than high values. Interestingly, though the mean is 1.38, there is a 41 percent chance that the true BCR will be less than 1.0, based on the simulation results. Consistent with the benefit estimates above, the minimum BCR is 0, but there is a negligible chance of such a result being obtained. The maximum BCR for this project is estimated to be 6.02.

This analysis does not preclude the analyst from presenting one number, as is currently done. For Heck Valley, the BCR is 1.4. The decision-maker does, however, have more options with this type of information available. For example, assume for the moment that the expected value of the Heck Valley BCR was 0.7. With traditional analysis, this means the project lacks economic feasibility and it is time to close up shop. The analysis here provides the decision-maker with the option of looking at this project differently. For example, suppose the results of this 0.7 BCR analysis showed there is a 25 percent chance of a justified project despite the apparent lack of economic feasibility. Managers can then decide whether it is worth pursuing a project with a one-in-four chance of proving to be feasible.

Indicating the probability that a project is justified could allow decision-makers to pursue strongly supported projects that would be precluded from further consideration under traditional methods. Analysts could report the probability of a justified project rather than or in addition to the single BCR estimate. Probabilities of returns would also aid program management decisions faced with allocating scarce budget resources over a number of projects. Net benefits, of

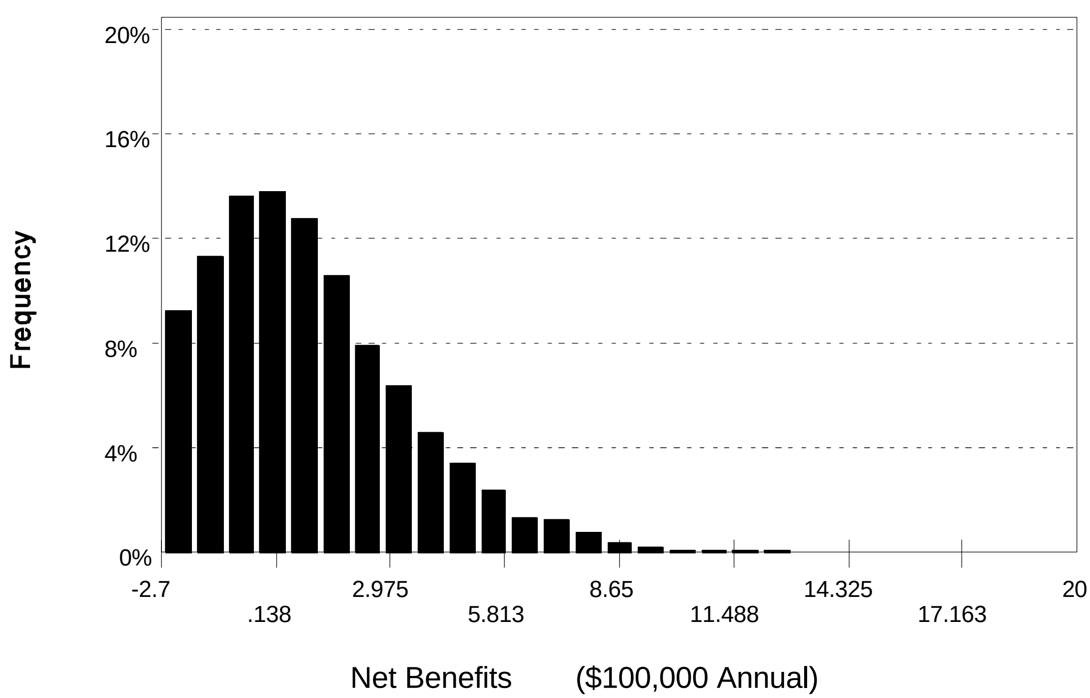


Figure 18: Net Benefits Frequency Histogram

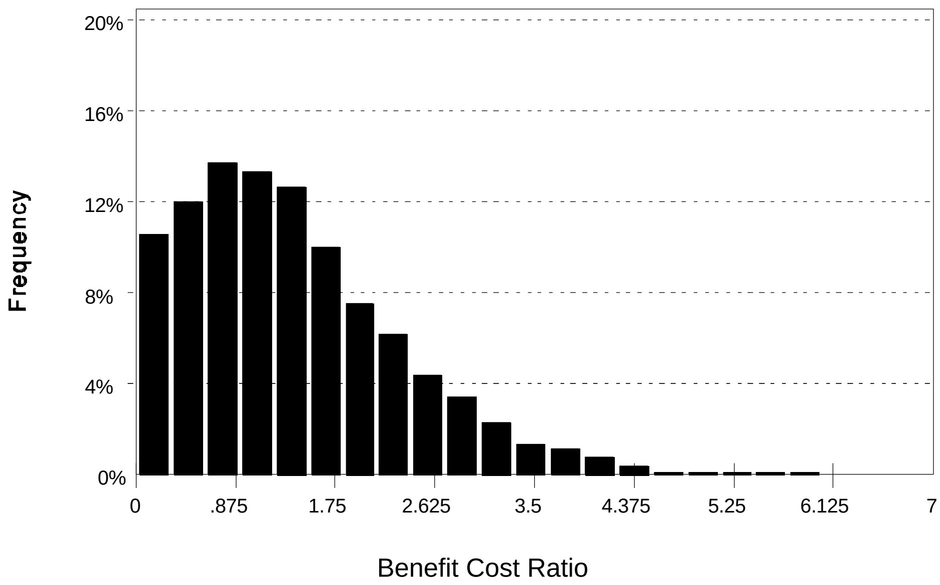


Figure 19: BCR Frequency Histogram

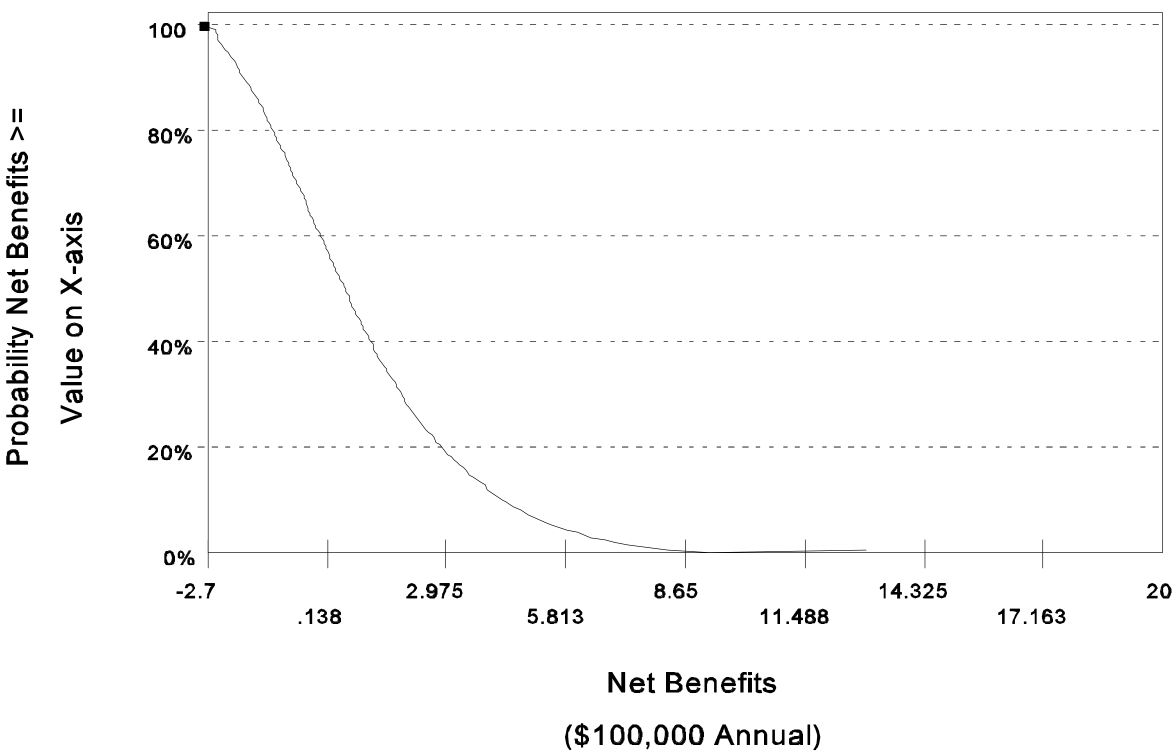


Figure 20: Net Benifits Cumulative Distribution

course, directly parallel the BCR results. There is a 59 percent chance of non-negative net benefits.

The simulation described above consisted of 10,000 iterations. Simulations of 4,000, 500, and 100 iterations were also run to provide some basis for comparison. Table 18 summarizes results obtained for the benefit-cost ratio, and expected annual damages without and with the project at various simulation sizes. Means do not vary significantly with the simulation size. In general, a reasonable estimate of mean values can be obtained with a modest number of iterations in models of reasonably well-behaved systems. However, information about and

Mean		1.38
Minimum		0.00
Maximum		6.02
Standard Deviation		0.93
Probability BCR	>= 0.0	1.00
	>= 0.6	0.73
	>= 1.0	0.59
	>= 1.2	0.42
	>= 1.8	0.20
	>= 2.4	0.08
	>= 3.0	0.03

Table 17: Distribution of Benefit-Cost Ratios

Item:	10,000	4,000	500	100
Benefit Cost Ratio:				
Mean	1.384	1.366	1.375	1.381
Minimum	0.000	0.000	0.000	0.012
Maximum	6.024	5.538	4.693	5.029
Range	6.024	5.538	4.693	5.016
Standard Deviation	0.960	0.955	0.979	0.950
EAD Without:				
Mean	$ 5,491	$ 5,444	$ 5,457	$ 5,061
Minimum	724	613	817	1,526
Maximum	17,230	16,288	14,818	14,326
Range	16,506	15,676	14,002	12,801
Standard Deviation	2,434	2,407	2,480	2,454
EAD With:				
Mean	$ 1,939	$ 1,939	$ 1,925	$ 2,048
Minimum	171	161	250	385
Maximum	6,378	6,542	5,440	4,954
Range	6,206	6,381	5,190	4,569
Standard Deviation	893	895	867	933

Table 18: Results from Simulations of Varying Size

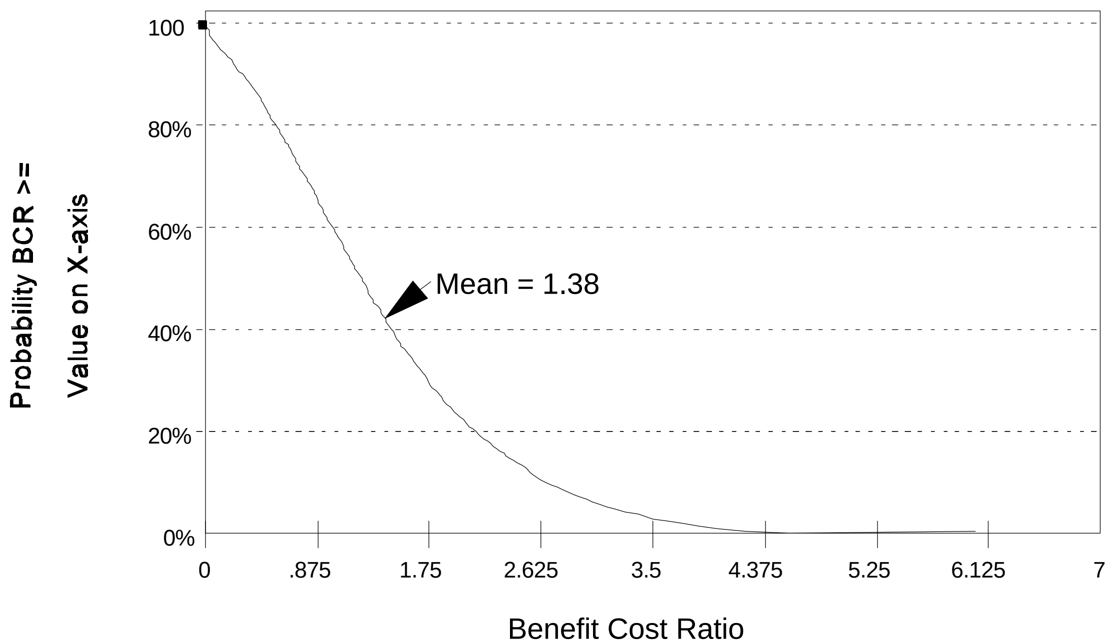


Figure 21: BCR Cumulative Distribution

observance of rare and extreme events cannot, generally, be obtained from small simulations. Hence, when information about extreme events (e.g., worst case/best case scenarios) is desirable, large simulations are necessary.

Land Subsidence and Freeboard

A levee subsidence problem, described earlier in the report as most probably corrected, has been identified as an important formulation issue in the Heck Valley. Comprehensive repair of the problem has been initiated and will be completed before the project base year. It is believed that the solution to the subsidence, instability, and seepage problems has been found. However, it is reasonable to consider that over a 100-year planning horizon, no engineering solution to such a complex and dynamic problem can be considered final.

The potential reappearance of a subsidence problem at some point in the future is relevant to the estimation of project costs if it is assumed that a lasting commitment to maintaining the integrity of the project has been made. The working assumption is that whatever repairs are necessary to "guarantee" the design level over the 100-year project life will be undertaken. The estimation of the uncertain costs of this situation is an important aspect of project uncertainty to be considered.

In the best judgment of the design engineers, the recurrence of a stability problem with the improved levee system would result in the need for major rehabilitation work such as is currently underway. It was estimated that this work would cost from ten to fifty percent of the initial first costs of construction.

The timing of a recurrence of the problem is clearly unknown. Two scenarios for a recurring problem were assumed. It was initially assumed that two episodes of levee subsidence are possible over the next 100 years. The first was assumed to occur sometime between project years 20 and 40, the second sometime between years 60 and 80. The second scenario is that one subsidence episode will occur, and it could occur anytime during the 100-year planning horizon.

Table 19 presents the results of a 1,000-iteration simulation of five cases for each of these two scenarios. The most important finding is that there is no significant effect on project formulation. Once the rehabilitation costs are discounted, they represent insignificant additions to project costs. As far as project costs are concerned, this analysis indicates that levee stability is not the issue analysts suspected it might be.

A general question about risk and uncertainty assessment arises. Given that a suspected issue turns out to be a non-issue (bear in mind that the subsidence issue is not finished), should the thought process be documented in the report? As always, the answer is, "it depends." If the issue is a relatively technical one, say concerning the value of Manning's **n**, the "non-results" are probably most usefully documented in project files. If the issue is one that is obvious to the decision-makers or the public, it should definitely be presented.

In the current instance, Corps' decision-makers will certainly be aware of the potential for such a problem. In this sense, "negative" results are of as much interest as any "positive" results would be.

Each of the scenarios included a no recurrence baseline simulation for direct comparison purposes. This allows the analysis to isolate the effect of the recurrence scenario and cost of

	One Episode Scenario:		Two Episode Scenario:	
Cost of Rehabilitation As % of First Costs:	BCR	Expected Annual Rehab Costs ($Million)	BCR	Expected Annual Rehab Costs ($Million)
No Episodes	1.38	0.0	1.4	0.00
20 Percent	1.46	1.6	1.41	0.06
30 Percent	1.35	2.5	1.40	0.09
40 Percent	1.32	3.3	1.39	0.12
50 Percent	1.30	4.1	1.37	0.14

Table 19: Project Cost Sensitivity to a Recurrence of Levee Instability

rehabilitation only.[38]

Freeboard Performance

An even more troublesome analytical problem is the issue of freeboard performance in the with and without condition and how it may be affected by future subsidence problems. The basic freeboard problem for economic analysis is: Will any flows in excess of the design flow be contained in the project freeboard? If so, which flows and how consistently will they be contained? The problem is one of accurately describing the with- and without-project conditions for the Heck Valley. Because flows in excess of design flows have been contained by the existing Heck Valley project and there is a history of land subsidence, the uncertainties inherent in this evaluation warrant more careful analysis.

The study area has an existing local flood protection project. Because the most feasible alternatives for flood protection consist of raising the existing levees and walls, a complex question of how to handle estimates of expected annual damages, and subsequently benefits, in the existing project freeboard and the improved project freeboard is introduced.

EM 1110-2-1601 has, in the past, guided design decisions about freeboard. Freeboard, by its nature, is an explicit recognition of the vast uncertainties confronted in designing a flood control project. Freeboard is an important planning issue for other reasons as well. Project costs depend on freeboard.[39] Benefits are determined by how well the freeboard functions. Even the level of protection can be influenced by the assumptions made about freeboard.[40] In the current example, estimation of benefits in the freeboard ranges is considered.

Current guidance allows for benefits claimed in the freeboard area to be one-half the total expected annual damages in the area between the design flow and the estimated maximum flow (top-of-levee flow) that may be safely passed. Freeboard benefits consistent with this guidance are currently estimated by calculating: 1) expected annual damages from any flow in excess of the design flow, and 2) expected annual damages with no damages from any flow equal to or below

---

[38] This case study makes extensive use of simulations to deal with the assessment of cumulative uncertainty and project risks. Simulations should be a last resort when analytical solutions to problems do not exist. Table 19 presents a good example of why this is so. The two-episode scenario with rehabilitation costs at 20 percent, results in a higher benefit cost ratio than does the no-recurrence scenario. This result is not logical. A careful review of the simulation failed to discover any errors in the simulation model logic. It would appear that chance alone has resulted in an illogically higher BCR for this case, or conversely, that a 1,000-iteration simulation was inadequate.

[39] One extra foot of height on a levee with a 5-on-1 side slope means the base of the levee is ten feet wider. Over a long distance, this can increase costs considerably.

[40] It is not unusual to hear things like: the design level is 50-year protection, the project has contained the 80-year event and top of protection is the 100-year event. In such cases, the Flood Insurance Administration may confine the 100-year flood plain to the channel between the levees, while the Corps maintains the community has 50-year protection. Which is it?

the maximum flow that can be safely passed. The difference between these two values is the expected annual damage in the freeboard. Half of these damages are project benefits.

In our hypothetical Tonsking example, under traditional estimation techniques, expected annual damages under existing conditions are difficult to estimate. Assuming damage from any flow greater than the existing levee design level, damages are $10,902,000. Expected annual damages, with no damage from flows below the top-of-levee flow, are $2,753,000. Expected annual damages in the freeboard range are $8,149,000. Interpreting this situation consistent with existing guidance, half of these damages are benefits to the existing project. The other half are assumed to be potential/existing damages. Thus, expected annual damages under existing conditions are $2,753,000 plus half of the $8,149,000, for a total of $6,828,000.

Keeping in mind that the current guidance was developed as a compromise in lieu of a better technique, risk and uncertainty analysis may well provide a better technique. In the case of Tonsking, the design level of 232,000 cfs was exceeded in 1985 when a flow of 252,000 cfs was contained by the project. In such a case, it is difficult to argue that any flow greater than design will cause damage. On the other hand, this flow was very near the top of protection at some points, and it is difficult to argue a flow of 290,000 cfs will surely be contained. Risk and uncertainty analysis may allow the analyst to make objective or subjective judgments about each increment of protection in the freeboard range.

Table 20 presents spreadsheet computations used for a traditional freeboard analysis. To keep the argument tractable, damages, flows, and frequencies are treated as if they are known with certainty. The only uncertainty, in this case, is the performance of freeboard. This allows the nature of the differences that occur with different freeboard assumptions to be observed.

In this example, it is generally agreed that the existing project will be 100% effective in containing the design flow. Thus, at MSL 547.7, damages are $0. H&H analysts are 80% certain flows will be contained in the first foot of freeboard, from 547.7 to 548.7. Although the next foot of freeboard is known to have contained a historical flood, analysts believe it is no better than a 60% chance that estimated flows in this range of freeboard will be contained. The next foot of freeboard has a 20% chance that flows estimated to be contained in this area will actually be contained by the project. The final foot of freeboard[41] has only a 5% chance of containing the estimated flows.[42]

To illustrate the use of this information, Table 21 contains the distribution of damages in the range of freeboard. For example, there is a 0.60 chance of $0 damage from flows estimated to fall within the 548.7 to 549.5 MSL freeboard and a 0.40 chance of $573 million damage.

---

[41] Levees in this area have more than the "normal" three feet of freeboard because of the potential for land subsidence.

[42] While the language used here may be uncomfortable to some H&H analysts, the important point is that analysts can put confidence intervals on the performance of freeboard on an incremental basis. They are no longer required to assess freeboard *in toto*.

Discharge 1000s cfs	Feet MSL	Frequency %	% Interval	Damages ($1000s)	Damages or Interval Avg.	Annual Damages Interval	Annual Damages Summation
228	547.7	2.200	NA	0	NA		NA
242	548.7	1.361	0.839	537,791	268,896	2,256	2,256
259	549.5	1.022	0.339	573,146	555,469	1,883	4,139
280	550.5	0.600	0.422	607,782	590,464	2,492	6,631
295	551.5	0.405	0.195	642,849	625,316	1,219	7,850
308	552.5	0.312	0.093	676,479	659,664	613	8,464
325	553.5	0.250	0.062	709,965	693,222	430	8,893
342	554.5	0.176	0.074	742,877	726,421	538	9,431
358	555.5	0.129	0.047	776,219	759,548	357	9,788
380	556.5	0.090	0.039	809,418	792,819	309	10,097
400	557.5	0.074	0.016	841,179	825,299	132	10,229
422	558.5	0.052	0.022	875,240	858,210	189	10,418
442	559.5	0.037	0.015	908,296	891,768	134	10,552
464	560.5	0.027	0.010	951,986	930,141	93	10,645
		0.000	0.027	951,986	951,986	257	10,902

Table 20A: Conventional Freeboard Estimation With Flows Greater than Design

Expected damages are 0.6 x $0 + 0.4 x $573,146, or $229,258. Expected annual damages using these expected damage values in the freeboard range are $6,638,000, slightly less than the $6,828,00 obtained under traditional methods.[43]

The latter approach forces damages to take their mean value in each and every case. This may or may not represent an improvement over the current guidance. Allowing damages to vary stochastically at each increment of freeboard represents a more realistic possibility than the above method because the performance of each increment of freeboard is independent of the other.

Using @RISK and the expected annual damage spreadsheet shown above, damages in the existing freeboard range were allowed to vary as shown in the text and table above. This first simulation[44] resulted in a mean expected annual damage of $6,638,000. Furthermore, given the

[43] The relatively close values are a result of chance, based on the probabilities used to describe freeboard performance. A different choice of probabilities could lead to a higher or lower than traditional estimate of expected annual damages.

[44] Under this approach, freeboard damages were randomly selected in each increment of freeboard, and expected annual damages were computed. The model restricted freeboard to a success (no

Discharge 1000s cfs	Feet MSL	Frequency %	% Interval	Damages ($1000s)	Damages or Interval Avg.	Annual Damages Interval	Annual Damages Summation
228	547.7	2.200	NA	0	NA		NA
242	548.7	1.361	0.839	0	0	0	0
259	549.5	1.022	0.339	0	0	0	0
280	550.5	0.600	0.422	0	0	0	0
295	551.5	0.405	0.195	0	0	0	0
308	552.5	0.312	0.093	676,439	338,240	315	315
325	553.5	0.250	0.062	709,965	693,222	430	744
342	554.5	0.176	0.074	742,877	726,421	538	1,282
358	555.5	0.129	0.047	776,219	759,548	357	1,639
380	556.5	0.090	0.039	809,418	792,819	309	1,948
400	557.5	0.074	0.016	841,179	825,299	132	2,080
422	558.5	0.052	0.022	875,240	858,210	189	2,269
442	559.5	0.037	0.015	908,296	891,768	134	2,403
464	560.5	0.027	0.010	951,986	930,141	93	2,496
		0.000	0.027	951,986	951,986	257	2,753

Expected Annual Damages in Freeboard Range: \$10,902 - \$2,753 = \$8,149

Table 20B: Conventional Freeboard Estimation With Flows Greater Than Top of Levee

distribution of results obtained from the simulation, there is a 53.1 percent chance that existing damages are greater than \$6,828,000. Table 22 presents some of the possible damage combinations in the freeboard range.[45] The first group of values presents a normal progression of damages. The second group of values shows some possibilities that result in illogical representations of damage curves. These are presented to illustrate an ever-present danger in using simulations. Simulation models must be carefully constructed and verified.

damage) or failure (full damages) trial, a restriction relaxed in a subsequent simulation. This process was repeated 1,000 times. The average of the 1,000 estimates of expected annual damages was computed and is used as the expected value of expected annual damages.

[45] Referring to Table 21 at elevation 550.5 MSL, damages are \$0 20% of the time and \$607,782,000 the remaining 80% of the time. The first simulation model is a naive one that lets the damage values at each elevation vary without regard to the value obtained at the preceding lower elevation(s). Thus, by chance it is possible to obtain a very logical progression of values or one of the many possible illogical progressions. Because of its logical flaws, this simulation may not improve the analysis at all over the currently prescribed method. This example, again, illustrates an important point--bad simulation can be worse than no simulation.

Range of Freeboard	Probability of $0 Damages	Probability of Positive Damages	Amount of Damages ($1000)	Expected Value of Damages
547.7 MSL	1.00	0.00	$ 512,499	$ 0
547.7-548.7	0.80	0.20	537,791	107,558
548.7-549.7	0.60	0.40	573,146	229,258
549.5-550.5	0.20	0.80	607,782	486,226
550.5-551.5	0.05	0.95	642,849	610,707

Table 21: Distribution of Damages in Existing Freeboard

To eliminate the possibility of illogical damage curves, the simulation model was modified. The second simulation allowed damages to vary according to the discrete values and probabilities of Table 21. However, the second simulation model provided logic checks that prevent damages at higher elevations from being less than damages at lower elevations. For example, if damages at 549.5 MSL in one iteration of the simulation were stochastically determined to be $573,146, and damages at 550.5 MSL in the same iteration were determined to be $0, the logic check would disallow the $0 at 550.5. In its stead, the damages at 549.5 would arbitrarily be increased 1 percent, and that value would become the 550.5 damages. Thus, any of the first group (Table 22) of damage curves is possible, but none of the second group is.

The second freeboard simulation has an expected value of $7,144,000. In this distribution of possible results, there is a 53% chance expected annual damages are greater than $6,828,000.

While the second simulation improves on the first it still only allows for an all or nothing performance by the freeboard. To demonstrate how simulations can be made increasingly realistic, a third simulation will be briefly described. It is not necessarily true that if freeboard does not contain the entire flow that damages will be the same as they would have been without protection. They could be less[46] or more.[47] To simulate this possibility the same probabilities presented in Table 21 are used; they represent the best judgments of our analysts. However, when flows exceed freeboard in the model, damages that result are no longer single discrete values. These damages have a distribution. For purposes of this illustration, damages at each elevation were assumed to be normally distributed. The logic of the second simulation requiring

[46] For argument's sake, consider a flood that just barely spills over the top of protection for an hour or so.

[47] Again, for argument's sake, consider the damages that would result from a sudden collapse of the protection.

MSL	Examples of Hypothetical Damage Curves				
547.7	$ 0	$ 0	$ 0	$ 0	$ 0
548.7	0	0	0	537,791	537,791
549.5	0	0	573,146	573,146	573,146
550.5	0	0	607,782	607,782	607,782
551.1	0	642,849	642,849	642,849	642,849
547.7	$ 512,499	$ 512,499	$ 512,499	$ 0	
548.7	537,791	0	0	537,146	
549.5	573,146	0	0	607,782	
550.5	697,782	0	607,782	0	
551.5	642,849	0	0	642,849	

Table 22: Simulation Damage Combination Possibilities

monotonic damages was used in the third simulation as well.

The expected value of the third simulation was $7,108,000. There is a 51.1% chance that expected annual damages are greater than $6,828,000. Table 23 summarizes the results of this analysis. In this particular example, there is little difference in the expected values. That is a chance result. It is also important to point out that this analysis has dealt only with freeboard uncertainty. The uncertainty of damages at elevations beyond the freeboard range has been ignored, as has uncertainty in the H&H work. Likewise, this analysis has not taken different assumptions about freeboard performance into account. The result in this example is that existing damages are higher than they would be under traditional methods in three of the four variations. The effect of this could be to increase potential project benefits. If all damages are eliminated by the project, benefits will be more.

It is important to realize, however, that in the more typical case of a levee or other flood barrier being constructed for the first time (as opposed to a project raising), the result of such an analysis could be to increase or decrease project benefits. No conclusions can be drawn from this example. The techniques of risk and uncertainty themselves are not biased toward higher or lower benefits.

A levee-raising project must deal with the freeboard issue for both the existing and improved conditions. There is arguably a distribution for expected annual damages for each of these conditions. In turn, there is a distribution for the expected annual benefits that are obtained by subtracting improved damages from existing damages. The estimation of benefits presented earlier treated freeboard consistent with the rationale of the third simulation using the analyst's best estimate of freeboard performance.

Item	Expected Value	Minimum	Maximum	Probability > Original	Probability < Original
Current Guidance	$ 6,828	$ 6,828	$ 6,828	0.00	0.00
Expected Value	6,638	6,638	6,638	0.00	1.00
1st Simulation	6,638	2,753	10,902	0.53	0.47
2nd Simulation	7,144	2,753	10,902	0.52	0.48
3rd Simulation	7,108	2,754	11,536	0.51	0.49

Table 23: EAD Estimates Under Varying Freeboard Assumptions

Modeling the performance of freeboard is only interesting insofar as it sheds light on the question of the project's feasibility and risk reducing capability. Five different freeboard performance scenarios were investigated. Table 24 summarizes the assumptions made about the freeboard in one-foot increments. Under the first set of assumptions, there is a 100% chance of no damage from flows estimated to be contained in the first foot of freeboard. There is a 90% chance of no damage and, conversely, a 10% chance of damages from flows estimated to be contained in the second foot of freeboard, and so on.

Table 25 presents the results of 1,000 iteration simulations for each of the new scenarios (1, 2, 4, 5). Scenario 3 represents the analyst's best estimate of the future with-project condition[48] and is used in the analysis shown above. The table reveals that freeboard performance is important to project feasibility. Although only one level of protection (290,000 cfs protection) is being considered, the same trend holds for all levels of protection investigated. If freeboard, particularly existing freeboard, functions better than the analysts expect (scenario 1), the project is no longer expected to be justified. Scenario 1 is the only scenario for which this is true.

Risk assessment brings us this far. To go on requires risk management. It is most likely that the decision about how to handle the above results will be made at the analyst or study team level. It could be the economist calculating expected annual damages, or it could be a number of

[48] The most probable future condition is rarely described completely in explicit terms in a report. Most of the assumptions about the most probable future condition are buried deep in the analysis of the project components. Here, a significant component of the future condition is revealed almost coincidentally. This provides a remarkable example of how risk and uncertainty management decisions are routinely made by analysts rather than by "decision-makers". Correspondingly, alternative future conditions can be carried forward in the planning process without them being made part of a soup-to-nuts description of a future that differs from the most probable scenario. In fact, it is far more likely that alternative future scenarios will differ in one or a few significant details rather than in every respect.

	Probability of Zero Damage Scenarios				
Freeboard Increment	1	2	3	4	5
1st Foot	1.00	0.90	0.80	0.60	0.40
2nd Foot	0.90	0.70	0.50	0.30	0.10
3rd Foot	0.50	0.30	0.20	0.05	0.00

Table 24: Freeboard Performance Assumptions

study team members.

There are a number of options for handling this problem. Scenario 3, the best estimate, could be used, noting that if freeboard functions like scenario 1 the project is unjustified. The case for the project is strengthened by noting that even if scenario 1 obtains, there is a 37 percent chance the project is justified. Alternatively, the study team could weight the probability of each scenario occurring. For example, they might determine that there is a 60 percent chance of scenario 3 and a 10 percent chance of each of the others. The weighted average, or expected value, of the BCR is thus 1.35. Weighting the probability of a BCR $\geq$ 1, a 61 percent chance of this event is obtained. Using the Laplace Criterion (see the Decision-Making Under Uncertainty Appendix to the Manual for Risk and Uncertainty Analysis in Corps' Civil Works Planning for more details), all five scenarios would receive an equal probability weighting. There is no shortage of ways to deal with this situation.

The risk management problem extends beyond consideration of different scenarios obtaining for a specific plan. The effects of these scenarios on the various plans need to be considered as well. Table 26 presents the mean benefit-cost ratio for the three alternative plans under each of the five freeboard scenarios. The results were obtained from 1,000 iteration

Item	1	2	3	4	5
Expected BCR	0.88	1.15	1.38	1.57	1.78
BCR at 5% Confidence	0.03	0.06	0.11	0.13	0.23
BCR at 95% Confidence	2.01	2.97	3.20	3.63	3.81
Probability BCR >= 1	0.37	0.48	0.59	0.65	0.71

Table 25: Benefit-Cost Ratios Under Different Freeboard Assumptions

Plan	1	2	3	4	5
290,000 cfs	0.88	1.15	1.38	1.57	1.78
340,000 cfs	0.75	1.05	1.23	1.40	1.69
450,000 cfs	0.89	1.11	1.14	1.34	1.55

Table 26: Alternative Plan BCR Sensitivity to Freeboard Scenarios

simulations, with the exception of the results for scenario 3. They are based on a 4,000-iteration simulation conducted earlier.

Choosing the best plan from this table is not a difficult problem. Nonetheless, it is useful to demonstrate the use of some decision making criteria from the above referenced appendix.

The LaPlace criterion weights each of the possible states of nature (scenarios) equally. The weighted average BCRs for the three plans are 1.35, 1.22, and 1.21, respectively. The 290,000 cfs plan is the best.

The maximin criterion chooses the plan with the largest minimum BCR--in this case, the 450,000 cfs plan (0.89). The maximax criterion selects the plan with the maximum largest BCR--the 290,000 cfs plan (1.78).

The Hurwicz criterion, using a coefficient of optimism of 0.5, yields BCRs of 1.33, 1.22, and 1.22, respectively.

The 290,000 cfs plans has a BCR higher than either of the other two plans under every scenario but the first. Thus, the dominance criterion cannot be applied other than to eliminate the 340,000 cfs plan.

Plan	1	2	3	4	5	Maximum
290,000 cfs	0.01	0.00	0.00	0.00	0.00	0.01
340,000 cfs	0.14	0.10	0.15	0.17	0.09	0.17
450,000 cfs	0.00	0.04	0.24	0.22	0.23	0.24

Tabke 27: Regret Matrix

The minimax or regret criterion likewise favors the 290,000 cfs plan. Table 27 presents a regret matrix. The cell values are the difference between the largest BCR for that scenario and each plan under that scenario.[49] These values represent the opportunity cost in terms of foregone BCR increases, i.e., dollars of annual benefits foregone for every dollar of annual costs, of choosing each plan should that scenario be obtained. The maximum opportunity cost for each plan is identified in the last column. The optimum plan is the one that minimizes this maximum opportunity cost or regret.[50]

In this case, there can be little argument that the 290,000 cfs plan is the best on most criteria and close enough to best on the minimax to ignore the difference. It is interesting to note that the different criteria can yield different rankings.

Table 26 illustrates the ease with which different states of nature (scenarios) can be systematically examined. What the decision sciences call different states of nature are easily interpreted in the Corps' jargon as alternative future conditions.

The analysts' overall conclusions are that freeboard performance can affect the economic feasibility of all plans. It does not, however, change the relative ranking of the plans. Under four of five scenarios, the plans are still economically feasible, including the scenario considered to be most likely, scenario 3. It is only under a relatively extreme assumption of maximum freeboard performance that the plans are not justified. For these reasons, the analysts concluded that freeboard performance, specifically, and land subsidence, generally, though considered significant issues through much of the study process, are not significant issues in the evaluation and formulation processes.

Induced Flooding

Communities upstream and downstream of the potential Tonsking project would have their flood problem worsened for floods higher than the physical capacity of the existing system in the Heck Valley and up to the physical capacity of any new flood protection system. Upstream areas will be flooded because of the "bottleneck effect" that will result in floodwaters backing up. Induced flooding occurs in adjacent areas because higher flood stages that currently overtop the existing Tonsking levees will no longer do so. The area of the land covered by the water is reduced, resulting in deeper levels of water on the remaining land and/or the flooding of land that would not have been flooded. In downstream areas, induced flooding occurs because with a higher levee system, some river flows would no longer overtop the levees. Storage would be lost and floodwaters would reach downstream communities sooner and with higher peaks than under existing conditions.

---

[49] For example, the 290,000 cfs plan under scenario 1 is 0.89-0.88 = 0.01.

[50] The regret matrix could have been based on differences in net benefits, project benefits, costs or any measure of interest to decision-makers. BCR was chosen over the more intuitive net benefits to demonstrate the flexibility of the concept.

		Additional Feet of Flooding at Indicated Discharge		
Community:	Location:	290,000	340,000	450,000
Sideriver	Downstream	0.1-0.4	0.3-0.9	0.8-1.5
Shinnyshick	Downstream	0.1-0.2	0.2-0.7	0.6-1.3
Wallopenwap	Downstream	0.0-0.2	0.1-0.5	0.4-1.0
Pyse	Downstream	0.0-0.1	0.1-0.3	0.3-0.8
Lockhem	Upstream	0.6-0.9	2.5-4.0	3.7-5.1
Kandor	Upstream	1.2-1.8	3.1-4.6	4.2-6.3

Table 28: Extent of Induced Flooding Problem

As a result of the altered nature of floods adjacent to and below the proposed projects, damages increase. The difficulties in addressing this problem are two-fold. First, there is considerable uncertainty involved in quantifying the problem. Data for areas outside of the immediate study area are necessarily less complete and reliable due to the reality of schedule and budget constraints. It simply was not possible to do detailed economic and engineering studies for each community potentially subjected to induced flooding. Second, the issue of how much mitigation to provide against induced flooding is a policy question with no clear precedents.

Table 28 presents a summary of the estimated extent of the induced flooding problem.

	290,000 cfs			340,000 cfs			450,000 cfs		
Community	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
Sideriver	1.0	2.5	4.0	0.0	3.3	7.7	0.1	4.8	12.2
Shinnyshick	0.4	17.1	32.6	0.5	23.5	54.1	0.6	37.5	88.9
Wallopenwap	0.6	9.1	19.3	0.2	14.4	35.6	0.1	18.6	50.1
Pyse	0.0	1.7	4.7	0.0	2.5	7.1	0.0	2.9	7.1
Lockhem	0.2	90.2	226.9	4.0	197.3	464.0	2.9	250.0	596.9
Kandor	12.7	121.5	224.4	17.1	277.3	610.0	25.3	364.1	732.5
Total	14.9	242.1	511.9	21.8	518.3	1,178.5	29.0	677.9	1487.7

Table 29: Expected Annual Damages Induced

The best estimate of the extent of induced flooding is the midpoint of the range shown. The hydrologic and hydraulic data used for this part of the analysis are of a lesser quality, hence there is considerable uncertainty associated with the quantification of the induced flooding problem.

Table 29 summarizes the estimated increase in expected annual damages that results from induced flooding. These estimates have been prepared using the techniques described in previous sections. The results reflect the uncertainty in the data. Minimum damages for the smallest raising are sometimes higher than the minimums for larger raisings. This results from the greater variance in variables for the larger plans.[51]

Induced flooding is a controversial issue in any planning study. A coherent treatment of all the policy concerns related to mitigating these damages is well beyond the scope of this case study. To handle this issue, our discussion will be restricted to considering induced damages as an economic cost of the project.

Table 30 presents the net benefits from each plan without induced damage costs and with induced damage costs. This sensitivity analysis shows that the 290,000 cfs plan is economically feasible under any foreseeable outcome. There is an effective zero probability of negative net benefits. The 340,000 cfs plan is not justified if maximum damages are observed. There is a 0.037 probability of negative net benefits for the 340,000 cfs plan. Under the most likely scenario, the 450,000 cfs plan is no longer feasible; it has a 0.929 probability of negative net benefits. Once the costs of induced damages are included, the 450,000 cfs plan is no longer economically feasible.

Induced flooding is a formulation issue that remains significant. It has the potential to affect the ultimate plan formulation and will be taken up again in the next section.

Induced Flooding Condition	290,000 cfs	340,000 cfs	450,000 cfs
No Flooding	$ 984.1	$ 745.8	$ 461.8
Most Likely	742.0	227.5	-(216.1)
Minimum	969.2	724.0	432.8
Maximum	472.2	-(432.7)	-(809.8)

Table 30: Alternative Plan Net Benefits With Induced Flooding

[51] This apparent illogical result could be easily rectified by truncating the distributions of key variables or filtering the outcomes to prevent results below some logical minimum.

PLAN SELECTION

The plan selection section of the report resolves the handling of significant issues. To this point, the major issues have been subsidence, freeboard performance, and induced flooding. It has been demonstrated that subsidence and freeboard performance do not affect the basic formulation and selection process. From an economic perspective, the feasibility and ranking of plans under the most probable future condition are not affected by the alternative future conditions that address subsidence and freeboard.

Induced flooding has an effect on the economic feasibility of plans that will come into play as the decision-makers deal with the risk management dimension of the risk and uncertainty analysis.

In order to select a plan from among the best alternatives, the basis of comparison will be the most probable future condition scenarios for each of the alternatives. The analysis done prior to this point has served to establish the overall lack of significance of what planners felt would be two critical issues.[52] There is no need to continue to carry all the possible combinations of

Item	290,000	340,000	450,000
1st Costs of Construction	$ 29,761.30	$ 38,416.30	$ 50,917.90
Annual Construction Costs	2,567.60	3,314.30	4,392.80
Annual O & M Costs	29.80	38.40	50.90
Induced Flooding Costs	242.10	518.30	667.90
Total Annual Costs	2,839.50	3,871.00	5,121.60
Total Annual Benefits	3,551.70	4,060.10	4,854.60
Net Benefits	712.20	189.10	-(267.00)
Benefit-Cost Ratio	1.25	1.05	0.95
Probability BCR>1	0.55	0.46	0.38

Table 31: Summary Economics of Alternative Plans Expected Values ($1,000's)

[52] That subsidence and freeboard ultimately were shown to have little impact on plan formulation and feasibility is not a trivial finding. Risk and uncertainty analysis was used to thoroughly investigate these issues. To have done otherwise would have left unanswered reasonable and significant questions about the importance of these two issues.

These issues were not considered as a joint risk problem in order to keep the example from becoming too complicated. In reality, land subsidence and freeboard performance are likely to be closely-related issues. The analysis of such a situation should be handled on a case-by-case basis.

scenarios and impacts forward through the selection step.

Table 31 presents a summary of the economic performance of the three alternatives. Considerable risk and uncertainty analysis has brought us to the point of presenting the information in the table. It is interesting to note, however, that this is the type of table decision-makers and Corps' personnel are used to seeing. It is easy to imagine the possibilities of reporting BCRs for numerous scenarios including alternative assumptions about subsidence, freeboard, induced flooding, stage-damage, hydraulics, hydrology, etc. There is no need to do so as long as the analysis has been objective.

Table 31 indicates that the 290,000 cfs plan is the NED plan. The 450,000 cfs plan is no longer justified. SPF protection would clearly be the emotional choice of the public because it provides the most protection. If there is support for such a project, the last line of the table could replace the benefit-cost ratio as the decision criterion. Although the analysts' best estimate is that this project is not economically feasible, there is a 38 percent chance that the true BCR is equal to, or greater than one. Of course, there is always the possibility that a reader could look at Table 31 and say there is a 45 percent chance the NED plan is not economically feasible.

Residual damages represent the analyst's estimation of the expected value of the flood damages that remain in the project area after a project is built. Table 32 shows that the nearly $2 million in expected annual residual damages for the NED plan is three times the level of residual damages from the SPF plan. The NED plan residual damages are about half a million dollars

Residual Damage:	290,000 cfs	340,000 cfs	450,000 cfs
Mean	$ 1,939	$ 1,460	$ 654
Minimum	172	164	0
Maximum	6,378	3,821	5,917
Critical Values:			
0%	172	164	0
10%	925	762	72
20%	1,193	967	126
30%	1,400	1,128	176
40%	1,595	1,269	246
50%	1,803	1,400	349
60%	2,016	1,546	506
70%	2,271	1,702	7,623
80%	2,609	1,911	1,105
90%	3,132	2,252	1,651
100%	6,378	3,821	5,917

Table 32: Residual Damages ($1,000's)

more than the Hilda-level (330,000 cfs plan) of protection.

The table provides some additional information, as well. The critical values relate to the cumulative probability distribution of residual damages. For example, there is 10 percent chance residual damages with the 290,000 cfs plan will be less than $925,000. Conversely, there is an 90 percent chance the residual damages are greater than or equal to $925,000.

This information allows comparison of damages with alternative plans at critical probabilities of occurrence. For example, there is a 90 percent chance that damages will exceed $925,000, $762,000, and $72,000 with the three plans. The decision-maker may identify critical probabilities and compare residual damages at these values rather than comparing expected values.

The decision-maker may establish some maximum acceptable level of residual damages, say, for example, $1,200,000, and compare the likelihood of obtaining that value. Although not shown in the table, it is a simple matter to use the distribution of with-project expected annual damages (i.e., the residual damages) to obtain these tail area probabilities. The probability of realizing residual damages of $1,200,000 or more are 0.80, 0.65, and 0.18 for the 290,000, 340,000 and 450,000 plans, respectively. It may then be possible to identify risk thresholds. For example, the decision-maker may decide that they will not bear more than a one-in-three risk (0.33) of maximum acceptable damages occurring. Each plan can then be ranked on such a criterion. In this illustration, only the SPF plan would provide less than a 0.33 chance of residual expected annual damages greater than $1,200,000 occurring.

Planning Objectives

Planning objectives have long necessitated the indirect consideration of risk and uncertainty. An objective of maximizing NED benefits, for instance, requires the type of analyses that are the subject of much of this case study. Risk and uncertainty should enter the planning objectives directly, as well.

In the case of the Heck Valley project, the basic concerns were to minimize the risk of flooding in the project area, avoid or minimize the creation of new risks, and to maximize our confidence in the results of our analyses. To these ends, the following planning objectives were identified to address these risk and uncertainty issues (original planning objective numbers are provided):

1. Reduce flood damages in those communities currently protected by the Federal flood control system.*
4. Reduce potential for loss of life.*
8. Reduce health hazards due to flooding.*
13. Avoid or minimize transfer of existing or creation of new risks, specifically, minimize induced flood damages and flooding in communities upstream and downstream of the study area.*
14. Minimize anxieties and concerns over flood threats.*
16. Achieve acceptable level of residual risk.*

Planning Objective	Plan 290,000 cfs	Plan 340,000 cfs	Plan 450,000 cfs
Reduce Damages	3	2	1
Reduce Life Loss	3	2	1
Reduce Health Hazards	3	2	1
Create No New Risk	1	2	3
Minimize Anxiety	3	2	1
Residual Risk	3	2	1
Available Information	1	2	3
Minimize Uncertainty	1	2	3

Table 33: Risk and Uncertainty Planning Objectives - Comparison of Alternative Plans - (Rank of Plan)

17. Make maximum use of available information and data.*
18. Minimize model, parameter, and other types of uncertainty.*

Table 33 provides a ranking of the plans' contributions to these objectives. All three plans reduce flood damages in the protected areas. The higher the level of protection, the greater the reduction in damages, potential loss of life, health hazards, anxiety, and residual risks. Higher levels of protection cause greater levels of induced flooding and potentially greater levels of damage in the event of project overtopping or failure. The lower levels of protection minimize model, parameter, and other types of uncertainty primarily because they require less extrapolation from existing data bases and other information.

Selecting a plan other than the NED is no longer easy to justify. In the Heck Valley, however, community sentiment is to provide protection from the flood of record. Knowing that the NED plan of protection would not protect them from a recurrence of the Hilda flood has resulted in a lack of enthusiasm for the 290,000 plan. The basic selection issue is the trade-off between economics and community acceptance. There are two dimensions to the issue of community acceptance.

First, there is the issue of an acceptable level of risk in the currently protected community. Second, there is the issue of induced flooding that is, predictably, vehemently opposed by the communities affected by the induced flooding. Acceptable residual risk is addressed in the following section.

Acceptable Residual Risk

Determining an acceptable level of risk presents a risk communication problem of vital importance to the community and the Corps. As part of the Heck Valley study process, numerous public meetings were held in a variety of locations. An effort was made in these meetings to discern the public's perception of the existing risk problem and to ascertain an acceptable level of residual risk.

A brief questionnaire used one or more of the following questions to discover the public's understanding of the existing flood risk.

(1) Were you living in Heck Valley at the time of the Hilda flood? YES NO
(2) If you answered yes to number 1, was your home flooded in 1972? YES NO
(3) Do you think your current home will be flooded in the next 30 years? YES NO

(4) Choose a year in the future so that you are 100 percent sure that by the time that year comes the Heck Valley will have been flooded at least once more.
____
(5) How many years do you think it will be between floods in the Heck Valley?
____
(6) How often do you expect Heck Valley to be flooded in the next 100 (also used 50) years? _________________
(7) What is the percent chance that there will be a flood in Heck Valley this year?
____
(8) What is the percent chance there will be at least one flood in Heck Valley during the next 30 years? _________________

The results of the questionnaires are presented in Table 34. The results consistently indicate

Item	Perceived Risk	Actual Risk
Flooded in Next 30 Years	141 of 171	NA
100% Sure of Flood by Year	2009	2089
Years b/w Floods (Average)	27	100
# Floods in Next 100 Years	4	1
% Chance Flood This Year	9	1
% Chance Flood in Next 30 Years	63	26

Table 34: Public Perception of Existing Flood Risk Summary

that the public overestimates the risk of flooding.[53] This indicated one of the first objectives of the public involvement program would be to educate people about the actual risk they faced.

This was done in an informational public meeting where the public was free to attend short concurrent sessions on a variety of topics, one of which was the risk of flooding. Here the approach used was to relate flood frequencies to a 30-year time frame, the typical term of a mortgage and a realistic time frame for the public. Experiments involving the public were used to illustrate a few key concepts.[54] The resulting improvement in understanding provided some basis for discussing residual risks, albeit with an unfortunately small audience.

Through use of a "risk wheel" with 99 chances of "no flood" and 1 chance of "flood", it was possible to communicate both the relative risk of flooding in any year and the independent stochastic nature of the events. The wheel was spun in 30-spin sets to represent a reasonable planning horizon for the public. At the end of the workshop, the total number of spins and "flood" events from all sets was reported to the attendees. The device seemed to effectively communicate the nature of the flood threat in Heck Valley.

The public involvement program included specific efforts to assure that local officials and decision-makers were included in all efforts to educate the public about their existing risks. In the latter stages of the public involvement programs, participants were asked to respond to the following situation:

> A friend of yours has told you he is considering buying a house on your street. He knows your community was flooded in 1982 and has asked you what is the likelihood of being flooded. How would you answer your friend?

The answers indicated that most people felt the threat of a flood in the near term future (say, the next several years) was minimal, if not negligible. In the longer term (generally construed to be sometime over the friend's lifetime in that location), people seem to expect to be flooded again <u>if</u> they had been flooded in 1982.

Despite the education efforts, people feel flooding is inevitable in their lifetimes with the existing level of protection. In the present, these same people cope with this threat by ignoring it.

Having established that people tend to overestimate the threat of a flood and undertaking efforts to correct this misperception through education, a second educational thrust of the risk communication program was to make one simple point: absolute protection from floods is impossible. On this score, the public involvement program was more successful. The public was

---

[53] The community is considered to have a 100-year level of existing protection. This assumed level of protection is the basis for the actual risk figures.

[54] The experiments were geared toward revealing the heuristics people use in assessing risks and the flaws inherent in their use. These heuristics are discussed in Volume I, <u>Guidelines and Procedures for Risk and Uncertainty Analysis in Corps' Civil Works Planning</u>.

constantly reminded that in this real world of scarce public funds and nature's hazards, no community can be made perfectly safe from the threat of flooding.

Some of the questions used to establish an acceptable level of residual flood risk include the following:

(1) There was a one percent chance of a flood in 1982. There has been a one percent chance of a flood every year since 1982. Is a one percent chance of a flood in any year acceptable to you? YES NO

(2) If you answered no to (1) tell me what percent chance of flooding in any year is acceptable to you? ________________

(3) Assume for this question that you are planning to live in your current community indefinitely and that flooding is the only factor that would make you move. Assume that if the chance of flooding in the next 30 years is zero percent, you will not move. Further, if the chance of flooding is 100 percent, assume you will move. At some percent chance of flooding, you will be unsure whether to go or stay. To the best of your knowledge, what is the percent chance of flooding in the next 30 years at which you are unsure whether to stay or move? (In other words, if the chance of flooding is a little less, you will definitely stay; if it is a little more, you will definitely move.)

____

Most people felt that a one percent chance of flooding was too much. This was likely a reaction to the juxtaposition of the 1982 flood and the one percent chance. The most common response to the first question was "no," followed by the answer "0" to the next question, indicating either that people did not grasp the reality that zero risk was not an option they had or that people actually defined "zero" as some very small finite number, e.g., .0001.

Results from the third question were more helpful. A difficulty with this question was that due to differences in topography, the respondents were not talking about one well-defined level of risk.[55] Due to the existing protection, however, essentially all of the respondents were assured of first floor flooding with any flood event. Thus, the difficulty presented by different topography and first floor elevations could be essentially ignored.

The average response to this question was a 10 percent chance, meaning that once the probability of being flooded rose above 0.1 over a 30-year period, respondents were, in a sense, indifferent between staying or moving. This information was used to infer an acceptable level of residual risk. Moving was considered to be a clear sign of unacceptable risk.

Using the binomial distribution, as adapted by Bulletin #17B <u>Guidelines for Determining</u>

[55] For example, say a person indicated that a 5 percent chance of flooding in the next 30 years was acceptable. If a second person, in an identical home on ground ten feet higher, said the same thing, they would be referring to a different event.

Desired Probability of No Flooding in 30 Years	Probability of Flood Event	Level of Protection
0.99	0.00033	2,985
0.95	0.00171	585
0.90	0.00351	285
0.85	0.00540	185
0.80	0.00741	135
0.75	0.00954	105
0.70	0.01182	85
0.65	0.01426	70
0.60	0.01688	59
0.55	0.01973	51
0.50	0.02284	44
0.45	0.02627	38
0.40	0.03008	33
0.35	0.03439	29
0.30	0.03934	25
0.25	0.04516	22
0.20	0.05223	19
0.15	0.06128	16
0.10	0.07388	14
0.05	0.09503	11

Table 35: Estimate of Acceptable Residual Risk

Flood Flow Frequency by the U.S. Department of the Interior, Table 35 was calculated. If a resident is just willing to accept a 10 percent chance of flooding in the next thirty years, that is equivalent to a desired probability of no flooding equal to 0.9. Formally, that is a 0.9 probability of zero floods in thirty years. A risk of this magnitude is achieved by a flood event with an annual exceedence frequency of 0.00351.[56] This is a 285-year event. Thus, as a first approximation, a 285-year level of protection is the minimum protection acceptable to the public that participated

[56] A 0.1 chance of one or more events in 30 years is equivalent to a 0.9 chance of no floods in 30 years. This latter probability is estimated by:

$$R = (1-P)^N$$

where: R is the probability of no floods, N is the number of years and P is the annual exceedence frequency. When R = 0.9 and N = 30, solving for P we obtain 0.00351. This is a 285-year event.

in the survey.

Table 35 presents the levels of protection consistent with different levels of acceptable risk. One minus the desired probability of no flooding in 30 years, obtained from the public, is the chance of flooding over a typical mortgage period at the floodplain location that would, hypothetically, trigger a person to move from the floodplain. This table illustrates a range of values and the concomitant levels of protection.

Residual risk is a complex topic for the layperson to understand. Efforts to explain and deal with the concept in direct probabilistic terms were unsuccessful. The study used indirect methods to infer risk preferences from the public's answers to a series of questions. In the stable ethnic Heck Valley communities, a 30-year planning horizon was suggested for the public. Using binomial probabilities and working backwards from the public's average preference for an acceptable risk of flooding in the coming 30-years, an acceptable residual risk was inferred; it was 285-year protection. The three plans offer varying degrees of protection. The 290, 330, and 450 plans provide approximately 420-year, 830-year, and 7,700-year protection.[57] All of the plans clearly provide at least the level of protection the public indicated it wanted. The results of this survey were predicated on the assumption that all floods were more or less generic in terms of the public's perception of them. In a protected community where any flood is catastrophic, by virtue of its overtopping the protection, this may be an acceptable simplification of reality. In an unprotected community, it would not be.

An alternative approach, when all floods are not alike, would be to query the public on the subject of acceptable expected annual damages. This might be done by posing questions about the maximum annual amount they would be willing to pay for flood protection. Possible payment vehicles could include: an annual fee for privately-funded flood protection, an annual tax to finance a project, or a hypothetical insurance payment that would remove the threat of flooding to some extent. The choice of payment vehicle would be extremely important in such a study.

During the study process, it was found that the perceived flood risk was much higher than the

---

[57] At this point, it should be obvious that statements about the level of protection are far from certain. Using the techniques illustrated in the presentation of expected annual damages, it is more realistic to reason as follows. A levee of a known height could provide protection against a range of flows. This range of flows depends on model assumptions (e.g., starting water surface elevations, Manning's **n**, etc.) and actual flooding circumstances (e.g., winds, waves, debris, etc.). Each flow in this range has some probability of occurring in a given year. That probability estimate itself has a range of values. Thus, the 290 plan provides protection from a flow estimated to be somewhere in the range of a 0.022 to 0.95 percent chance of annual flooding, with a most likely value of 0.24 percent. The most likely level of protection is 1/.0024, or about 420-year protection. The range in protection is from 105 years (an unacceptably low level by our analysis) to about 4,500-year protection.

The estimated levels of protection for the 330 plan ranges from about 190-year to 11,000-year protection, with a most likely value of 830-year. The 450 plan level of protection ranges from about 1,100-year to 50,000-year protection, with a most likely value of 8,300-year protection.

actual flood risk. A measure of success was achieved in educating the public to their actual risk. Fairly reasonable estimates of acceptable residual risk were obtained, and all alternatives provide an acceptable level of residual risk. Unfortunately, the majority response is the desire for zero residual risk and no chance of damages from a recurrence of the flood of record.

Induced Flooding

Exacerbating a flood problem in another community is going to be unacceptable to that community no matter how slight the exacerbation. Creating new risks or increasing existing risks is going to be completely unacceptable to the affected community.

Induced flooding is a complex policy issue with many possible solutions. Some possibilities include:

1) *No mitigation*. Let the sponsor decide the desirability of the trade-off between reduced risks in one area and increased risks in another.
2) *Mitigate expected annual damages*. Provide mitigation measures that insure that expected annual damages with the project are no more than expected annual damages without the project. This option maintains the community's level of risk, but could result in losers and winners within the community.
3) *Complete mitigation*. Provide mitigation measures that insure that no one is made worse off with the project than they were without the project. This would avoid the creation of winners and losers.
4) *Betterment*. Provide mitigation measures that insure no one is made worse, while taking advantage of any cost-efficient opportunities to decrease the existing risks to other communities. This could provide for increases in the levels of protection for existing communities.
5) *Indemnification of damages*. Provide for payment to the affected communities an amount equal to the capitalized value of the expected annual damages caused by induced flooding. This payment may be made in any number of ways, including cash payments for use by the community in flood mitigation, subsidized flood insurance, buy-downs on loans to flood-proof homes, etc.

To keep this example reasonably tractable, it has been assumed that there would be either no mitigation or an indemnification of damages. In the former case, expected annual induced damages are an economic cost only. In the latter case, they are both economic and financial costs. Their treatment is the same in either case.

Risk and uncertainty analysis techniques demonstrated to this point could be applied to an induced flooding analysis quite readily. The costs and benefits of mitigation measures can be estimated in much the same way. Issues of level of protection, residual risks, etc., can likewise be estimated.

RECOMMENDED PLAN

The recommended plan in this case study is the 290 NED plan. From a risk and uncertainty standpoint, this plan has a high probability of being economically feasible--it minimizes the creation of new risks and the transfer of risks (i.e., induced flooding is least with this option); the level of protection is expected to be in excess of 400-year protection and results in an acceptable level of residual risk. The most likely probability of a flood exceeding the design level of protection occurring over the 100-year project life is 0.214, with a range from 0.022 to 0.615. The most likely probability of a flood exceeding the design level of protection over a 30-year period is 0.07, with a range of 0.007 to 0.249.

Although the NED plan is not designed to contain a Hilda-level event, it is expected that the

Number of Years	Highest p (p=0.0053)	Most Likely p (p=0.0012)	Lowest p (p=0.00002)
100	0.412	0.113	0.009
70	0.311	0.081	0.006
50	0.233	0.070	0.005
30	0.147	0.035	0.003
10	0.052	0.012	0.001
5	0.026	0.006	0.000

Table 36: Probability of Floods Exceeding Protection

Hilda event would be contained within the freeboard. The best estimate of the top of protection flow is 330,000 cfs, the Hilda flow, based on estimates of the probability of flows that would reach top of levee heights, ranging from 0.00009 to 0.0053, with a most likely value of 0.0012. Table 36 presents the probabilities of one or more floods exceeding the top of levee during selected time periods. Thus, for a 100-year period, there is a 41.2 percent chance of one or more floods exceeding the top of levee if the actual annual probability (p) of that flow is 0.0053. Likewise, there is an 11.3 and a 0.9 percent chance of overtopping and damages if we use the most likely and minimum probabilities, respectively.

Referring to the results of some of the study's risk attitude surveys, it was found that the recommended plan most likely presents a 3.5 percent chance of flooding over a 30-year period. This is well below the residents' estimate of 10 percent as the risk that would leave them indifferent between living with the flood risk and moving from their homes. Only under the most extreme circumstance (highest p value) would the risk exceed the 10 percent level. At the other extreme, the risk of flooding is less than 1 percent with the lowest p value.

Communicating this information to the public is well beyond the scope of this example risk and uncertainty analysis. With time and experience, however, it is entirely reasonable to expect that such notions can be incorporated routinely into Corps' investigations and reports.

Part II

NAVIGATION

NAVIGATION

INTRODUCTION

The Star City Navigation Case Study is a hypothetical study prepared to illustrate and support the principles and selected techniques described in the Guidelines and Procedures for Risk and Uncertainty Analysis in Corps' Civil Works Planning and its accompanying Appendices. Real data from Corps' projects are used wherever possible in order to represent realistic situations. Where real data were not available, data have been fabricated. The data and issues presented in the case study do not represent or depict any past, present, or future Corps' project or study.

The case study begins with an overview of the hypothetical study and proceeds through the six planning steps:

1) Specification of problems and opportunities;
2) Inventory and forecast;
3) Evaluation;
4) Detailed evaluations;
5) Detailed analysis; and
6) Plan selection.

Risk and uncertainty issues that could be confronted during each of the planning steps are raised and addressed in turn. The purpose of the case study is to demonstrate risk and uncertainty analysis techniques in a manner that is accessible to most Corps' planners. Although state-of-the-art techniques are often used, advanced theoretical or statistical methods are not relied on in this particular case study. The case study, while not written in the style of a typical Corps' report, is sufficiently "reader-friendly" in such a way as its style can be readily adapted to the Corps' report style.

OVERVIEW

Star City is located on the Keepemat Bay, a large inland bay on the coast. It is served by an existing navigation project that was initially completed in 1950 and subsequently enlarged in 1968. The existing authorized project provides for a 40-foot deep channel to Star City. Project width is 400 feet. Crude oil imports are the sole commodity that would utilize a deeper channel. The existing project was designed for vessels up to 40,000 deadweight tons (DWT) and was expected to be sufficient for traffic through the year 2015. However, within just 15 years, vessels as large as 80,000 DWT routinely navigate the Star City channels.

A study to determine the need for, and advisability of, improving the Star City project was authorized. That study is the subject of this case study. Additional details of the project will be provided on an as-needed basis as the case study proceeds.

SPECIFICATION OF PROBLEMS AND OPPORTUNITIES

In this initial step, the critical elements for a good risk and uncertainty analysis include:

1) Problem identification;
2) Understanding public views;
3) Understanding public attitudes about risk and uncertainty; and
4) Establishing specific risk and uncertainty planning objectives.

The emphasis of thought, at this point in the study process, is to eliminate, minimize, or document as much uncertainty in the planning process as possible.

Problem Identification and Understanding Public Views

Navigation studies are particularly vulnerable to the temptation to identify "solution-defined" problems. Pilots, port authorities, state and local governments are often sophisticated expert groups who have appraised the situation, from their exclusive viewpoints, and reached a consensus of opinion on the problem's definition and solution.

In Star City, the initial interest in the planning study came from the Star City Port Authority (SCPA), a quasi-public agency funded by the state government. Their interest grew out of the Star City Pilots Association's concerns for safety, after the frequency and severity of navigation accidents began to increase through the 1970s. The growing reputation as an unsafe port has caused some shipping lines concern, when faced with decisions about expansion in, or continuation of services to Star City. These concerns, and an increasingly competitive market for waterborne commerce, led the SCPA to identify the problem as the need for a wider and deeper channel into Star City. To support their problem, they offered the following issues as evidence:

1) **Safety**. Vessel operators have noted a decreasing margin for error in navigating the project and an increasing number of accidents. A large number of recent accidents or, in the navigation jargon, "casualties", involved channel banks or another vessel. The channel is generally deemed too narrow.

2) **Delays**. Constrained channel widths into the Star City harbor cause a variety of delay problems. These delays include restrictions to daylight-only or one-way traffic for certain size vessels and restrictions on meetings, passes, or overtakings.

3) **Competition**. Star City authorities are well aware that a number of competitor ports are constructing or planning deeper channels. They want to remain competitive. Pilots and shippers report that they receive weekly requests to bring vessels, currently restricted from the channel, into the port.

To the Corps' analyst, this type of problem identification is all too familiar. The channel is not wide or deep enough. The solution is to make it larger. Many times the local interests even know how large the improved channel has to be. The purpose of the planning process is simply to legitimize the conclusions of an important, but select, group of people.

Analysts should treat the locals' identification of the problem as the judgment of, perhaps, the best-informed interests in the planning process. They should, however, avoid accepting it as a definitive identification of the problem. One cannot be sure the problem is adequately addressed until the problem is adequately defined.

To identify the problem adequately, it is necessary to understand the public's views. The pilots are, quite naturally, concerned about safety. They captain the vessels brought through the project. Their livelihoods and licenses are on the line in the event of a casualty. They are under substantial pressure to bring larger and larger ships through the project. They need not be concerned about paying for the project or the environmental damage a project could cause. Port authorities and government agencies are concerned about jobs, income, tax base, and competition. They know they have to satisfy the pilots' and Coast Guard's safety concerns, but economic development is their main concern.

These are important concerns, but they do not necessarily constitute problem identification. It is the planner's job to understand the various points of view and to clarify the problem. In reality, the contents of a Corps' report are politically sensitive. There are some things that just cannot be said. In a case study, reality is not a constraint. Although some of the things that follow cannot be said in a report, they should, if true, always be understood. In the Star City study, the problem identification section of the Main Report included the following:

> The problem in Star City is a complex one. Because recent development in the Star City area exceeded everyone's expectations, as a result of the change in energy markets over the past two decades, the area finds itself with a port inadequate to meet current and projected future needs. Much of the development, particularly along the waterfront, proceeded without adequate thought given to sensible land use plans. Landside development now represents one of Star City's most severe constraints to future growth.
>
> The rapid development of the waterfront in the absence of a long-range plan for the development and growth of the Star City Harbor has produced a rather schizophrenic use of the port. Areas closest to the downtown's central business district and two residential communities along the project's waterfront have been developed as marinas for over 2,000 recreational craft. The mix of vessels operating within the project area includes ocean-going and non ocean-going vessels, tows and barges, mineral supply vessels, commercial fishing vessels, bay workboats, houseboats, and naval vessels in addition to the recreational craft.
>
> Traffic congestion and the lack of a more unified and comprehensive Vessel Traffic Service (VTS) system have contributed to a significant increase in the number of accidents within the project area. Unanticipated changes in world-wide energy markets have resulted in a world fleet of vessels, ever-increasing in size. Neither the size of the vessels nor the magnitude of the commerce currently

moving through Star City were anticipated.

As a result, the existing channel dimensions are inadequate for Star City's current market for navigation services. The increased traffic congestion, reckless antics of recreational craft, larger vessels, etc., combine to produce a very small margin of error for ship operators. In an effort to minimize the casualties that result from this diminished margin of error, a variety of delaying tactics are either required or are voluntarily invoked.

One victim of the unregulated growth in Star City has been the effective loss of aids to navigation. Range lights tend to get lost among the city lights and traffic. Buoys are frequently out of place.

The existing navigation project is not unanimously revered despite its huge impact on the local economy. There are a large number of environmental problems associated with the project. Habitats are changed and disrupted as a result of periodic dredging. Wetlands and other habitats are lost in the existing disposal areas. Open water disposal of dredge material is routinely challenged in court. Spills of petroleum products and other hazardous materials have occurred in the past. Although there have been no major spills, the Valdez spill has heightened concern about the impacts of a major spill on the Star City area and on the corresponding sensitive areas and resources of the Keepemat Bay.

Understanding the various public views cannot be done passively. Planners cannot rely on newspaper coverage or mailing lists to identify a problem. You have to talk to people. In the Star City study, focus groups were used to help identify the problems from the outset of the study. Groups of like-minded people were assembled and engaged in both directed and free-wheeling discussion of the problems and opportunities presented in the Star City project area. Each group tended to see the situation, and therefore to define the problem, from a rather narrow focus. From the various groups, a more coherent and much more complex picture of the problem arose.

The brief problem description above provides a different view of the problem than is typically obtained. The problem is most definitely not the existing channel dimensions. It is significant to note that many of the existing problems were brought upon the area by a lack of planning. The lack of a port plan has resulted in a port that has an incompatible mix of vessels. Planning for the future must clearly address effective controls on the numbers and operation of recreational craft and such matters as perhaps a choice between ocean-going and intra-port tow traffic.

A comprehensive plan must also address landside development in the Star City area. It is essential to avoid the problems of the past in the future. This will require local land use planning, zoning, etc. There appears to be some indication that progress can be made now to address the safety and delay problems through VTS or other navigation guidelines.

It is critically important to identify the problems that exist already as a result of the existing project. The environmental problems identified provide planners with a better understanding of what the more controversial concerns about any project improvements might be. Significantly, this is done early in the study to allow maximum opportunities for issue resolution during the planning process. A more certain identification of the problem promises a more predictable implementation of the solution.

Failure to adequately identify the problem can lead to a planning process that is tightly guarded from the public. Too often, an inadequate problem identification leads to a plan developed in concert with too narrow a circle of interests. The plan is presented to the public at a series of meetings, the Corps takes its shots from the public and then proceeds with the plan, only to have it side-tracked by a lengthy series of court challenges.

Not all problems identified throughout the study process are of equal magnitude, but all deserve some attention. For example, the following problem was identified during the initial study efforts:

> Traffic to Star City has been steadily increasing in numbers and size since the 1950s. Waves and backwash generated by passing ships have grown larger and more destructive as traffic has increased. Accelerated erosion rates on the northern tip of Jones Island have resulted. County Road 177, used primarily by residents of Load's Point and school buses, may soon be lost as the island's cliff-like shoreline continues to erode.

This Section 14-type problem does not deserve equal billing with the larger scope problems, but it should not be ignored in a thorough identification of the study area's problems and opportunities.

Public Attitudes about Risk and Uncertainty

It is evident there are things we don't know and can never know when we undertake a study. It is likewise obvious that any project entails tradeoffs between risks alleviated and risks created. Navigation projects have a long history of litigious challenges, and planners are well-advised to understand the risk and uncertainty attitudes of the various public interests. Equally important is the need to educate the public about the risks they face, the relevant risk and uncertainty issues, and the realistic options for dealing with them.

What are the levels of risk the community is willing to bear? How much delay will shippers accept before changing operations? How wide a channel is safe enough for the pilots? What is an acceptable level of risk for a Valdez-like oil spill? Are more numerous small spills more or less acceptable than the risk of a large spill?

Who will answer the above questions, and how will they arrive at their answers? Experience teaches that no planning process, no matter how open and objective it is, can resolve all issues for all interests. Nonetheless, a concerted effort to identify the risk attitudes of the various participants early in the study provides maximum opportunity to formulate plans to address those concerns or to undertake public involvement programs to ameliorate those concerns.

While understanding public attitudes about risk is primarily a listening process at the outset, successfully addressing these attitudes requires ongoing two-way communication. It is important to establish early in the process that zero risk is not a realistic option. "No delay" is not achievable. Complete safety is a fiction. Oil spills, even major ones, will never be an impossibility. Effective consensus cannot be reached on any plan until participants understand this fundamental point.

Risk and Uncertainty Planning Objectives

Typical planning objectives are identified to provide a basis for measuring the performance of alternative plans and comparing them to one another. To aid risk and uncertainty analysis, it is advisable to identify objectives for the planning process. Some of the typical planning objectives for the Star City study include the following:

1) Improve the level of navigation safety;
2) Improve economic efficiency;
3) Improve environmental conditions;
4) Minimize adverse environmental consequences.

The first and fourth objectives inherently embody risk and uncertainty analysis. A good risk and uncertainty analysis requires specific planning objectives. Examples of risk and uncertainty objectives for Star City alternatives follow:

5) Educate the public to the impossibility of zero risk;
6) Inform the public about basic risk-benefit tradeoffs of plan;
7) Achieve an acceptable level of risk;
8) Clearly identify residual risks;
9) Minimize model, parameter, and other types of uncertainty.

Many of the above objectives could be made more specific. For example, number 7 could say, "Achieve acceptable level of risk of oil spill of 500,000 gallons or more." The specificity of the objectives would largely depend upon the problem identification.

Objective 5 should be accomplished for all study participants regardless of the alternative. It should be clear with each alternative that risks may have been reduced, but they have not been eliminated. What may vary is the type of risks present with the alternative.

Study participants should be aware of the risk-related tradeoffs that are being made in each alternative. Pilots must understand that wider (hence, safer) channels mean higher costs (hence, larger financial obligations for local sponsors and citizens). Wider channels mean more dredge disposal and increased risk to sensitive ecological resources like oyster beds and wetlands. Where possible, the analysis should identify the marginal risks associated with the marginal benefits of any decision.

Achieving an acceptable level of risk is purposely vague at this point in the study; it is impossible to identify what the critical risk issues are going to be or what an acceptable level of risk is. Likewise, identifying residual risks is non-specific. Objective 8 is closely related to Objective 5. If the study succeeds in convincing the public that zero risk is impossible, it succeeds in creating an obligation to identify the risk that remains with each alternative.

Objective 9 recognizes that there is much that we do not and cannot know. Some plans will require us to operate more in the realm of the uncertain than will others. This objective identifies those plans that contain less uncertainty than others. For example, an eleventh hour compromise alternative may have to be presented without benefit of the detailed analysis other alternatives have received. In some cases, grab samples may be available from a channel bottom; in other cases, core samples will be available. The latter provides more information about bottom conditions and leads to more certainty in disposal decisions, channel side-slope design, project costs, etc.

INVENTORY AND FORECAST

During this planning step, analysts concentrate on gathering and analyzing data. The focus of the risk and uncertainty assessment is clearly on the assessment stage. Emphasis in this step should be placed on honestly reporting the tentativeness of our knowledge about the resources in the study area. Rather than presenting precise numbers, that in truth lack certainty, ranges of values should be used. It is not always possible to explicitly state the level of confidence we have in our data. The range of values presented can serve the same purpose subjectively by the mere fact of the interval width; i.e., a narrow best estimates range will generally indicate a greater degree of confidence than a wide best estimates range, provided the ranges are established in an unbiased manner. These ranges can be chosen by the analyst to represent her/his degree of belief in the actual data.

In this step, the critical elements for a good risk and uncertainty analysis include:

1) Identify key risk and uncertainty issues and important variables.
2) Preliminarily identify methods to address risk and uncertainty in the study.
3) Identify multiple without-project condition scenarios.

Existing Conditions

Existing condition sections of study reports are often long litanies of facts gathered during the study process that may be of interest to someone, somewhere along the study review chain. Emphasis in describing existing conditions should be given to identifying those resources relevant to the problems identified, the analyses conducted, or the plans formulated. There is no need to report the age of housing in a deep draft navigation study.

Most navigation studies do require a substantial amount of physical data. Geology, mineral and groundwater resources, bathymetry, salinity, water temperature, tides, waves, erosion rates, shoaling rates, air temperature, ice cover, rainfall, storms, winds, terrestrial and aquatic habitats, threatened and endangered species, commercially or recreationally valuable species, and sensitive ecological areas (e.g., wetlands, oyster beds, rookeries, nesting areas, spawning areas, etc.) are among the conditions that would typically be described in some detail.

Some of the descriptions rely on descriptive statistics, others on statistical inference. Frequently, the data used to describe the study area may be of different vintage and quality. This can be frankly acknowledged in the report as shown by this introductory paragraph from the existing conditions description:

> Data describing the existing conditions have been obtained from a variety of sources. Some have been obtained from investigations conducted during this study. Other data are file data from the 1950 and 1968 projects. Some of the data have been obtained from secondary data sources, i.e., publications and files of other agencies. Although the origins of some of these data are not known, the sources of the data are considered reliable and we believe the data to be the best available.

While the content of this simple paragraph is wholly unremarkable, it does represent a significant step forward in risk and uncertainty analysis. It is a first step out of the denial phase. It is the beginning of an acknowledgement that we do not know everything. The hope is that anyone who finds the quality of the data used unacceptable will be willing to pay for improvements to the data base. If the quality of the data is an issue that leaves the study vulnerable to serious challenge, then that data becomes an important uncertainty issue and a key variable in the analysis.

Acknowledgment of the tentativeness of our knowledge should be carried forward throughout the study process. Not all of this, however, needs to be presented in the report. The vast majority of data and analysis and, consequently, the risk and uncertainty assessment and management, will be found in project files. The simple act of conveying the reality of a lack of certainty can be conveyed consistently in subtle ways as follows:

> Erosion of the bay shorelines results from the interactions of wind, waves, currents, water level changes, geologic activity, sediment loading, ship waves, and storms. Typical shoreline recession rates in the vicinity of the project vary. Average erosion rates range from 5 to 7 feet per year. Recession rates for dredge material disposal islands average 15 to 18 feet per year.
>
> The average recession rates have been obtained from surveys conducted at irregular intervals over the last 70 years. The erosion does not occur in neat increments of 5 feet or 7.5 feet per year. In some years, there has been accretion to some shorelines. In other years, storms have removed large portions of the shoreline. Table 1

Location	Average Rate	Recorded Minimum	Recorded Maximum	Standard Deviation
Load's Point	17.8	3.8	40.2	9.3
Shortchester	5.0	(1.7)	11.4	6.3
Worserton	7.2	0.8	15.6	7.7
Heart & Liver Island	15.5	12.3	23.0	5.9

Source: Aerial photographs, newspapers, surveys, & anecdotal evidence.

Table 1: Erosion Rates for Selected Locations

presents a more realistic summary of the recession rates at selected locations in the study area.

The first paragraph above is an example of the most common way of addressing existing conditions at present. Analysts may well understand the reality described in the second paragraph, but most decision-makers and many other readers will not. If erosion is a significant issue in the study, it is important to describe it more adequately and admit that the erosion rate is a matter of some uncertainty. The simple addition of the second paragraph does that.

There are a variety of techniques for presenting the uncertainty inherent in much of the data used in a study. It can be performed in text as in the above write-up. Table 1 uses data from a variety of sources of unequal credibility, but it establishes the point that erosion is not a steady, predictable process. Figure 1 provides yet another look at the variability in erosion rates that create uncertainty in the annual erosion rate.

A variety of techniques are available to convey the variation in important variables. The expanded description, table, and figure are readily adaptable to most any variable. Specialized techniques like frequency curves for streamflow, wind roses, real time tide plots, etc., can be useful presentation devices.

While risk and uncertainty analysis is still being incorporated into the planning and reporting process, it is advisable to provide a relevant interpretation for the more significant uncertainty that is being presented. For example, Figure 1 is accompanied by the following paragraphs:

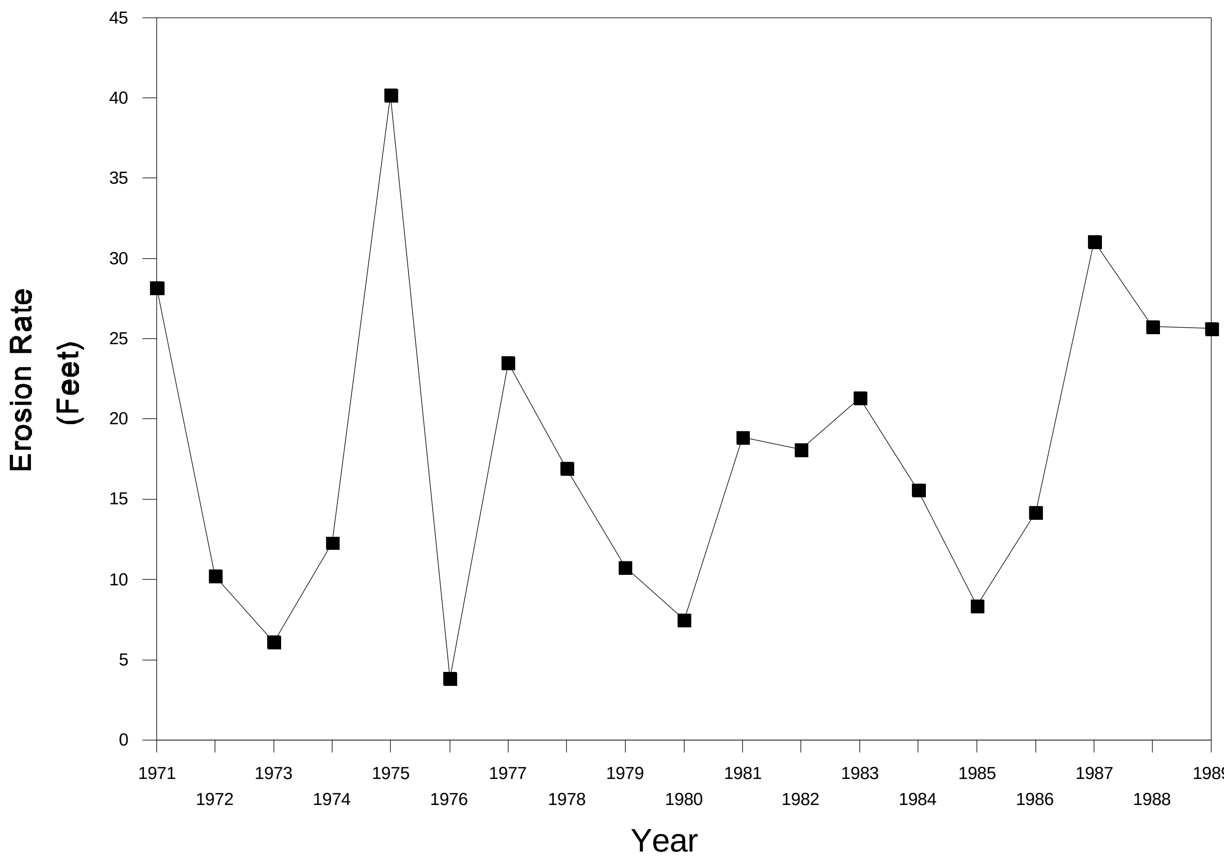


Figure 1: Annual Erosion Rates at Load's Point

As Figure 1 indicates, the erosion rate at Load's Point has varied considerably from year-to-year since measurements were started in 1971. Interestingly, the average rate of 17.8 feet per year has never been observed.

The current shoreline is about 95 feet away from County Road 177 at the closest point. Clearly the existence of this road, once hundreds of feet from the shoreline, is threatened. If the erosion rate were known with any certainty, we could easily forecast the time at which the road would be affected. Figure 1 shows us the erosion rate is not known with certainty. The average erosion rate is virtually useless in identifying the date at which the road will be lost.

Using the average rate, loss would occur in about 5.3 years. At the maximum observed rate, the road would be claimed by the Bay in about 2.3 years. If the minimum rate is maintained, the road is safe for 25 years. Thus the road could be gone in as few as 2 years or as many as 25 years. Based on recent average erosion rates, the road is most likely going to be lost within 5 years.

The relevance of all this is that the road is at risk and we don't know how long it will last.

Admitting the limits to our knowledge in such straightforward fashion is a vast improvement over the traditional presentation of a single best estimate.

In describing the existing ecology of the study area, it is important to identify critical issues and variables. At times it may be equally important to indicate that there are no critical issues or variables in describing the environment. In the case of the Star City project, there are no critical habitat designations for threatened or endangered species in or near the project area. Sensitive ecological areas do exist.

The inventory of the existing economic resources and activities is typically more detailed for a navigation study than it is for flood control. The structure and evolution of the economy are important for the future of the port. As with the ecological resources, it is important to identify those that are of critical importance.

A typical existing conditions inventory of ecological and economic resources might well be followed by a section such as this one from the Star City report:

> CRITICAL ISSUES AND KEY VARIABLES
>
> No critical habitat areas for threatened or endangered species are located in the project area. The oyster beds at Dutch Ship reef have been identified as an ecologically and commercially important resource that needs protection. Rather than one or a few resources of particular importance, the Star City area has a number of significant ecological resources. These include upland, swamp, marsh, aquatic and beach ecosystems.
>
> There are two major issues touching these resources. First, and foremost, are concerns regarding the effects of a major oil or other hazardous material spill on the delicate ecological systems. Second are the effects of dredging and dredge material disposal during project construction and maintenance dredging on the ecology.
>
> The major economic issue in this study concerns the magnitude and type of commerce moving through the port. The two most critical economic variables related to this issue are commodity movements and vessel traffic. These, in turn, depend significantly on land use patterns in the area and basic economic conditions.

These paragraphs serve the simple purpose of identifying key variables recognized early in the planning process. As the study begins, there may be an incomplete understanding of what the key variables and critical issues are. They will surely vary from study-to-study. Nonetheless, it is easy to anticipate the nature of many of the critical issues and key variables. This becomes even more true when the problem has been thoroughly identified.

The significance of these key variables will be addressed in later stages of the planning process. For example, vessel traffic will be extremely important in understanding and analyzing project benefits.

Future Conditions

Forecasting future conditions with and without a plan is fundamentally an exercise in risk and uncertainty assessment. The primary risk and uncertainty objective in this step is to give close attention to those key variables already identified and to identify assumptions that could significantly affect plan formulation. Some of these variables and assumptions will be buried deep in the minds and decisions of analysts. Some will be documented in study files. Others will be evident in the report.

As shown in the "Guidelines and Procedures for Risk and Uncertainty Analysis Flood Control Case Study", subtle changes in the language used to describe future conditions is an important first step in incorporating risk and uncertainty analysis in the planning process. In this case study, we emphasize the need to avoid the appearance of certainty in describing future conditions.

The best judgment of the Corps of Engineers (COE) was that the project constructed in

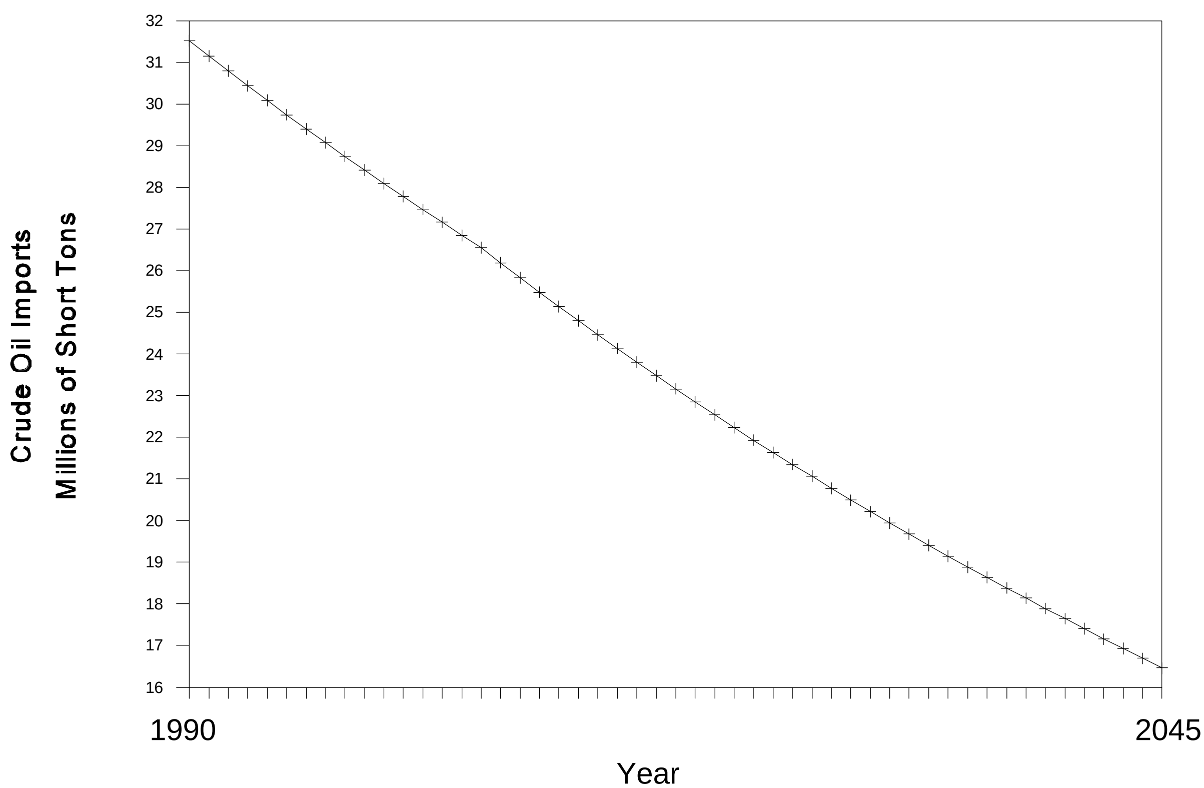


Figure 2: Most Likely Crude Oil Forecast

1968 would be adequate for the needs of Star City for 50 years. Within 10 years, it was evident that there were serious problems. The problems may have resulted from unregulated growth in the area or unanticipated changes in world energy markets, but the result was that the Corps' judgments were wrong.

A typical Corps' report presents a most likely future without-project condition. For example, forecasts of crude oil imports for Star City would appear as shown in Figure 2. This most likely forecast is based on an adaptation of the National Waterways Study baseline scenario (1981). Declining oil imports is a very popular scenario among energy experts. However, actual crude oil imports in the future depend on the availability and price of substitute fuels, the real price of oil, refinery capacity, production costs, conservation efforts, technology, lifestyle changes, geopolitics, national politics, recessions and recovery from recessions, and other factors.

It is naive to present a single forecast, and few Corps' reports do. There is no one, certain future condition, and this is nowhere more evident than when an analyst is asked to forecast something like crude oil imports 50 years into the future.

The primary method for dealing with this issue has been to present arguments for the preferred forecast and against others. Sensitivity analysis may or may not then be used to estimate benefits under other forecast scenarios. This is a reasonable approach to the problem of uncertainty. The single most significant change in approach used here is to indicate from the outset that the most likely forecast is one of many possibilities. The following are excerpts from the Star City report:

> Table 2 presents a summary of a number of credible crude oil import forecasts for Star City Harbor. All forecasts were prepared by experts in the energy and forecasting fields. The scenarios vary in significant ways. Some show a declining level of tonnage; others show an increase.
>
> Some of the scenarios assume a significant portion of domestic crude oil and increasing tonnage of foreign oil will be moved through Star City. Others assume no domestic oil imports and decreasing foreign oil imports due to continued conservation efforts, technological improvements, increasing reliance on other energy sources and increasing real prices of oil.

The report would, at this point, discuss the basic assumptions of each scenario in detail. The subtle, but significant, difference in approach is that the most likely future scenario, though identified, is never separated from the pack. Rather than Figure 2, a report following good risk and uncertainty analysis techniques would present something like Figure 3 as the following excerpts indicate:

Forecast Years:

Alternative Forecast Scenarios:	1995	2000	2010	2020	2030	2040	2045
Most Likely	31,524	29,742	26,550	20,216	20,216	17,649	16,456
T G3-2	24,389	20,595	18,798	16,594	14,649	12,931	12,113
T G3-3	21,582	19,765	16,209	15,112	12,658	10,358	9,257
T G3-4	14,447	10,618	8,457	8,543	7,091	5,640	4,914
T G3-5	24,041	23,180	20,497	17,826	15,511	13,501	12,562
T G3-6	16,906	14,033	12,745	11,257	9,944	8,783	8,219
T G3-7	20,487	18,732	15,608	13,516	11,711	10,150	9,415
T G3-8	13,352	9,585	7,856	6,947	6,144	5,432	5,072
T G3-9	24,217	26,092	32,387	39,225	46,159	53,372	57,014
T G3-10	27,230	30,395	37,987	46,355	55,006	63,777	68,181
T G3-11	19,730	19,516	22,131	24,976	28,139	31,480	33,188

Table 2: Alternative Crude Oil Import Forecasts

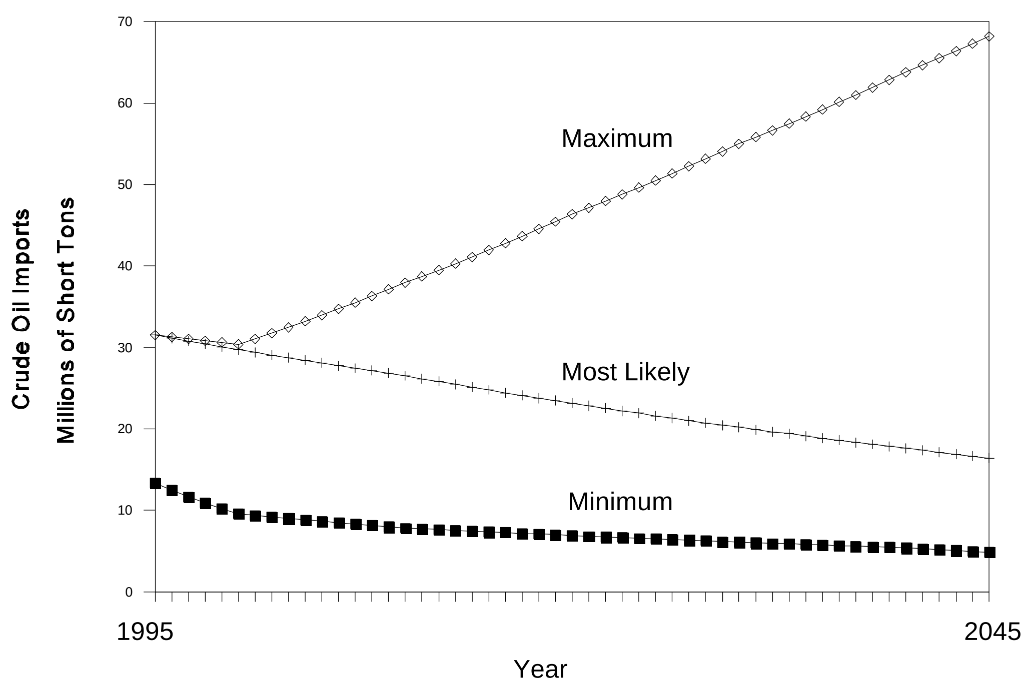


Figure 3: Minimum, Maximum, & Most Likely Crude Oil Forecasts

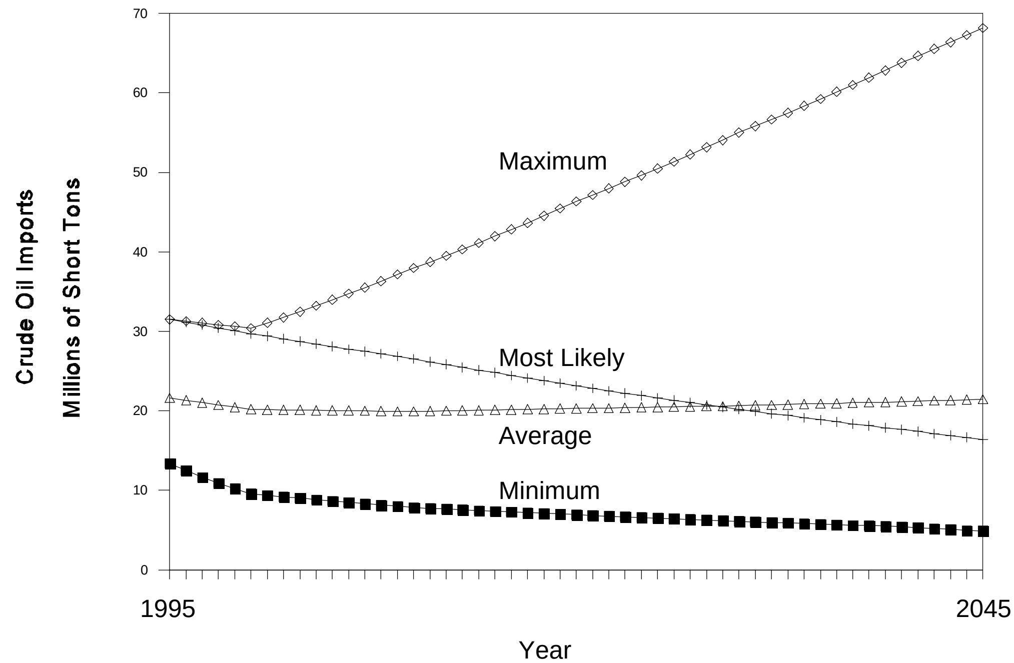


Figure 4: Minimum, Maximum, Most Likely & Average Crude Oil Forecasts

Figures 3 and 4 provide graphic summaries of the various crude oil import future conditions. Figure 3 presents the most likely future condition bracketed by the minimum and maximum estimates of tonnage for each year in the forecast period. Figure 3 indicates that the most likely forecast is far less optimistic than many of the scenarios that show slower declines in imports or actual increases in imports.

Figure 4 repeats the information from Figure 3, adding the average forecast. This average is simply the mean of the eleven forecasts presented in Table 2. It shows a rather constant level of imports that is considerably below the most likely forecast for the first 30-35 years of project life.

Why would an analyst choose the most likely scenario, "one", in Table 2, rather than one of the others? The reasons will vary from study-to-study, but they frequently have a great deal to do with such concerns as what a higher authority will accept. The Corps' credibility suffers when districts, some in the same divisions, use different forecasts as the basis for their project analysis.

A frequently cited reason for the selection of a particular scenario is that it is "conservative." But why choose a conservative estimate? Is it to gain acceptance of a higher authority? To avoid the criticism of opposition groups? Neither of these is a good analytical reason for the choice.

Figure 4 presents a range of forecasts prepared by experts. What is not evident is that

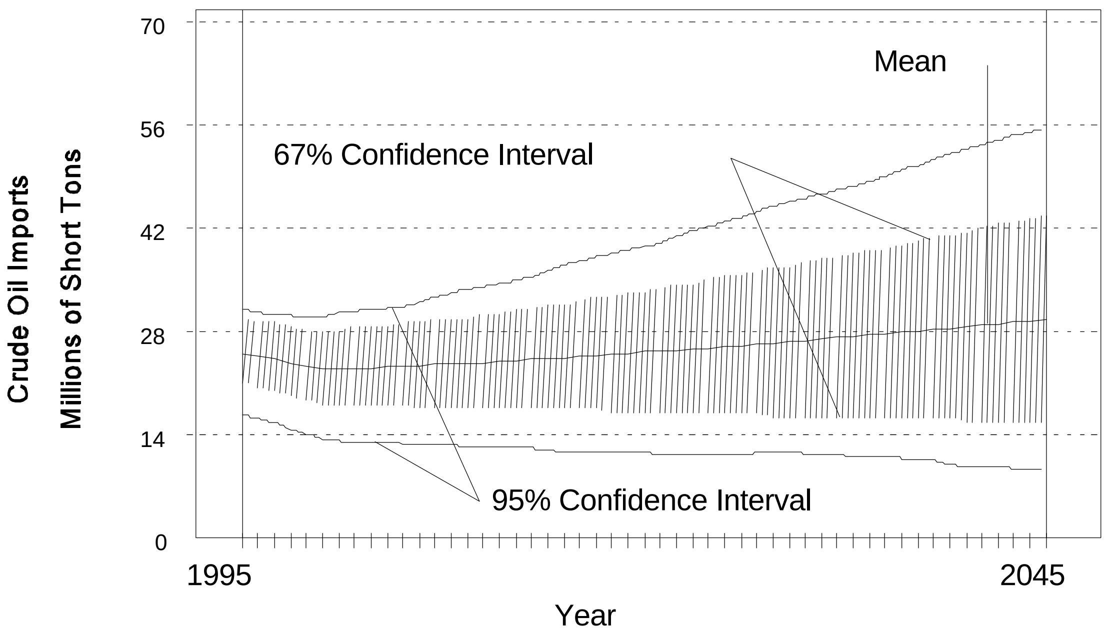


Figure 5: Crude Oil Forecast Simulation

Figure 4 is actually a three-dimensional figure rising up from the page. Its boundaries are described by the maximum and minimum forecasts. Its height dimension is a probability distribution centered over the "average" line. Thus, for any tonnage between the minimum and maximum forecast in any year, there is a unique height above that point corresponding to its probability of being realized.

A forecast based solely on the most likely future scenario may be justified if, in fact, that scenario is most likely and is not being used to meet other subjective criteria. In most cases, however, there is no advantage to ignoring the information contained in the other credible, if less likely, forecasts. Figure 5 presents the results of a crude oil forecast simulation using the information contained in Figure 4.

Table 2 presents the minimum, most likely and maximum tonnages[1] assumed for selected years. For the year 1995, it was assumed that the minimum tonnage measured in millions of short tons would be 13,352. The maximum was assumed to be 31,524, and the most likely tonnage was the same in this instance. The actual probability distribution of tonnages in this range is unknown, so a triangular distribution[2] was assumed. Triangular distributions were

[1] The most likely tonnage is presented in scenario one. The minimum is the lowest tonnage forecast for that year regardless of scenario; it generally comes from scenario eight. The maximum forecast comes from scenario ten, with the exception of the forecast for 1995.

[2] A triangular distribution is frequently used when better information is not available. The triangular distribution specifies a distribution with three points--minimum, most likely and maximum values. The direction of the skew of the distribution is set by the size of the most likely value relative

assumed for each of the years indicated in Table 2. Forecasts can be simulated from this information.

A tonnage forecast for 1995 was randomly selected from the triangular distribution. Forecasts for subsequent years were correlated with this initial forecast to assure some degree of consistency in the forecast values. Values for the years between those randomly selected were interpolated based on a compound annual growth function.[3] Figure 5 presents the forecast mean and the distribution of values obtained in the forecast just described. The 67 and 95 percent

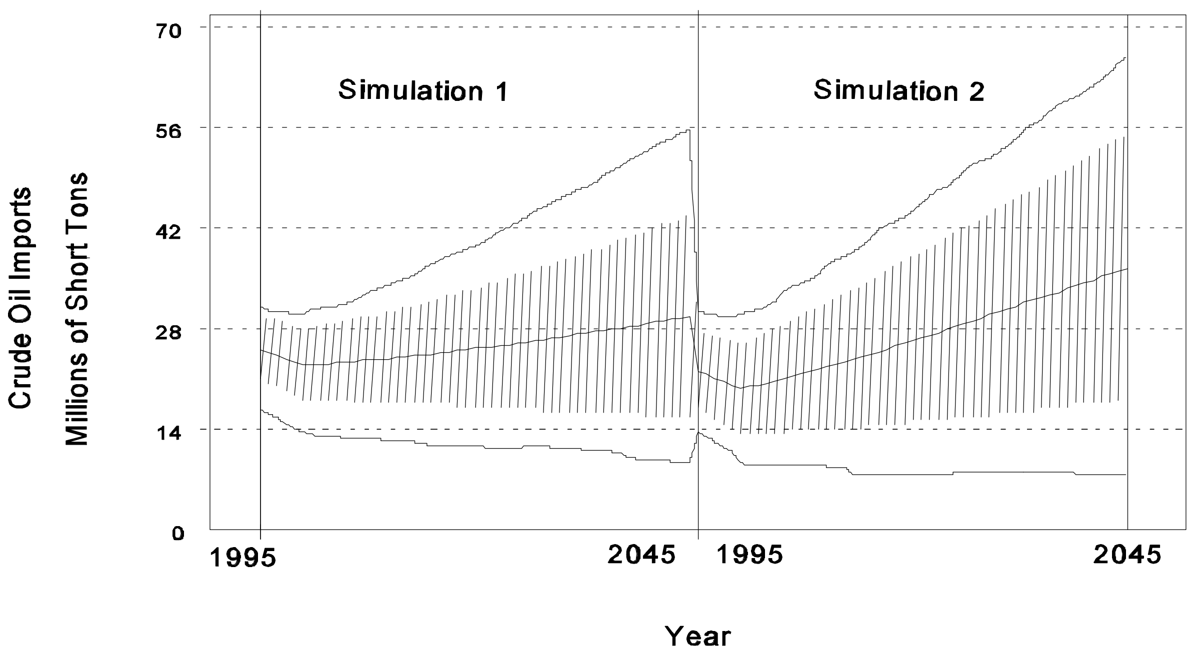


Figure 6: Comparison of Oil Forecast Simulations

confidence intervals are also presented. The mean of this simulation is arguably a better forecast of future tonnage insofar as it takes a greater quantity of credible information into account than does a single most likely forecast. It represents a synthesis of numerous future conditions.

The simulation results depend on the underlying assumptions and structure of the

---

to the minimum and maximum values. The probability of the minimum and maximum values is zero. Thus, if it is important that the extreme values can be obtained, it is advisable to select a minimum arbitrarily smaller than the true minimum and a maximum arbitrarily larger then the true maximum.

[3] Appendix A presents a sample of the cell formulas from a Lotus spreadsheet that used the @RISK add-in. To reproduce the entire spreadsheet would be redundant.

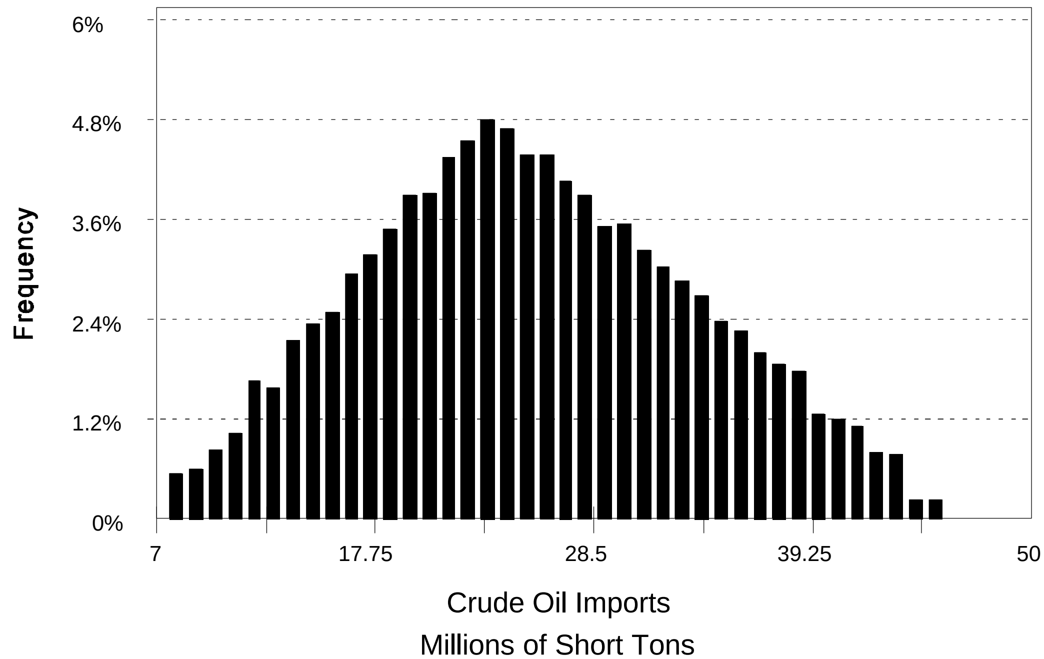


Figure 7: 2020 Crude Oil Forecasts Triangular Distribution Frequency Histogram

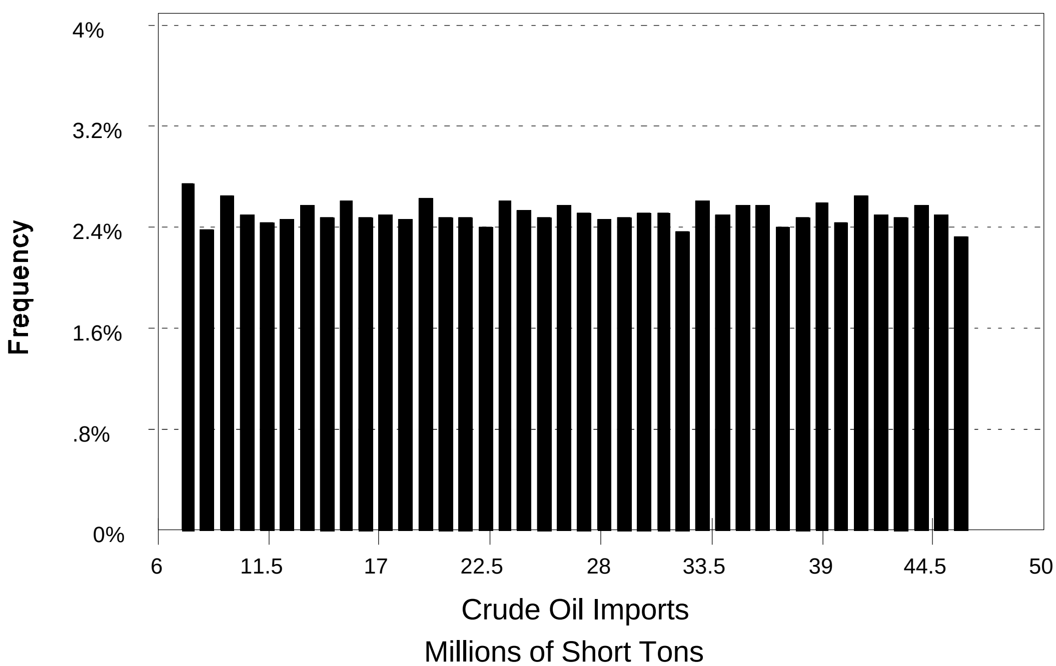


Figure 8: 2020 Crude Oil Forecasts Uniform Distribution Frequency Histogram

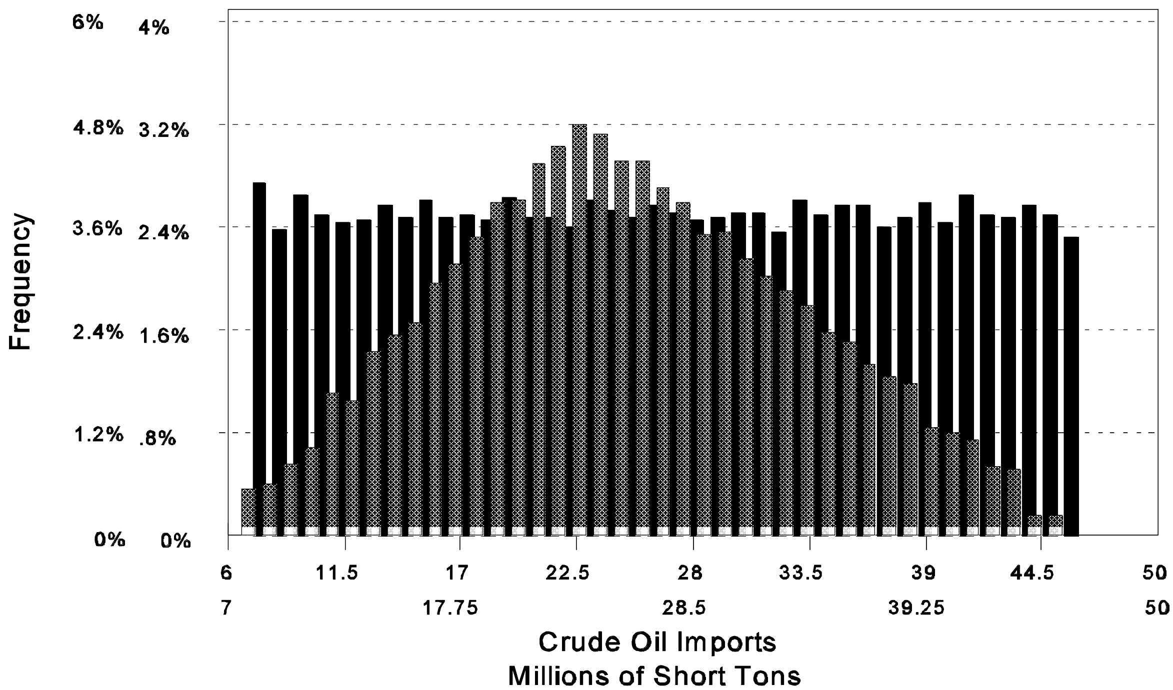


Figure 9: 2020 Crude Oil Forecasts Superimposed Distributions Frequency Histograms

simulation. The minimum, most likely and maximum tonnages were identified and assumed to have a triangular distribution.[4] Figure 6 presents two crude oil forecast simulation scenarios. In the first simulation (left half of the graph), tonnage forecasts are assumed to be triangularly distributed. In the second simulation, the tonnages were assumed to have a uniform distribution.[5]

Figure 6 indicates that the underlying assumption about the distribution of forecasts can make a significant difference in the simulation results. The confidence intervals are wider for the assumed uniform distributions, and the means take a different path over time.

Like Figure 4, both Figures 5 and 6 each represent three-dimensional figures. Figure 7 shows a frequency histogram for crude oil forecasts for the year 2020 based on the triangular distributions shown in the first simulation of Figure 6. Tonnages range from about 7 to 45 million short tons of crude oil, with the mean around 23-24 million. The most frequently observed

[4] It is possible to specify any number of distributions for future tonnage. All eleven forecasts could be incorporated into the simulation, if so desired. One method for doing this would be to construct a simple frequency histogram in which the probability of each individual forecast being obtained is specified.

[5] In a uniform distribution, any value between the minimum and maximum values specified has an equal probability of being selected. There is no "most likely" case.

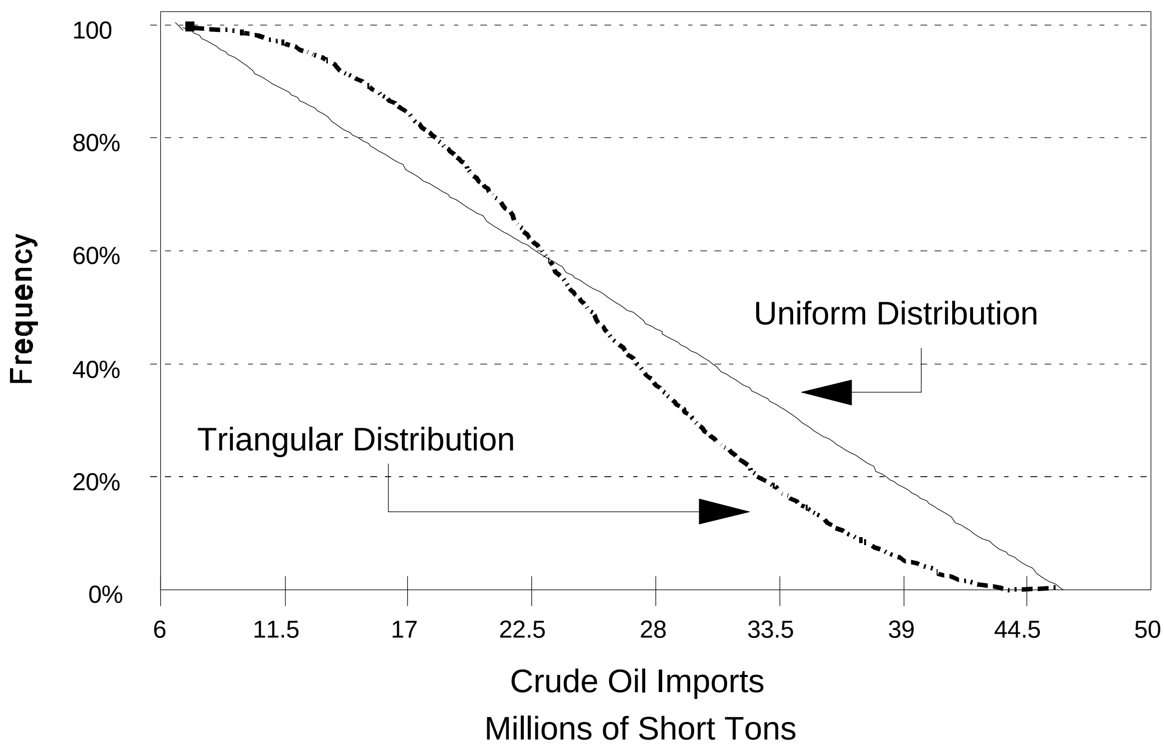


Figure 10: Cumulative Distributions of 2020 Forecasts

tonnages are in the neighborhood of the 23 million tons identified as most likely (see scenario one in Table 2), but tonnages significantly greater and significantly less are clearly possible and have been observed in this 500-iteration simulation.

Figure 8 shows the distribution of forecasts for 2020 based on an assumed uniform distribution. Figure 9 superimposes the two histograms to illustrate the differences. The range in tonnages is about the same, but the likelihood of extreme forecasts is much greater with the uniform distribution.

Figure 10 presents another comparison of the year 2020 forecasts. The cumulative distributions present the same information contained in Figure 8 in a different form. The vertical axis shows the frequency with which the forecast tonnage, shown on the horizontal axis, was equalled or exceeded during the 500 iteration simulation.

The comparison shows that 80 percent of all tonnages forecast under the triangular distribution assumption are greater than or equal to about 18 million tons, while 80 percent of forecasts under the uniform distribution assumption are greater than about 15 million tons. The uniform distribution has more relatively low forecasts. Alternatively, the figure shows that about 87 percent of all triangular forecasts equalled or exceeded 17 million tons, while only about 75 percent of all uniform forecasts did. At about the mean of both distributions, this relative relationship in forecasts reverses.

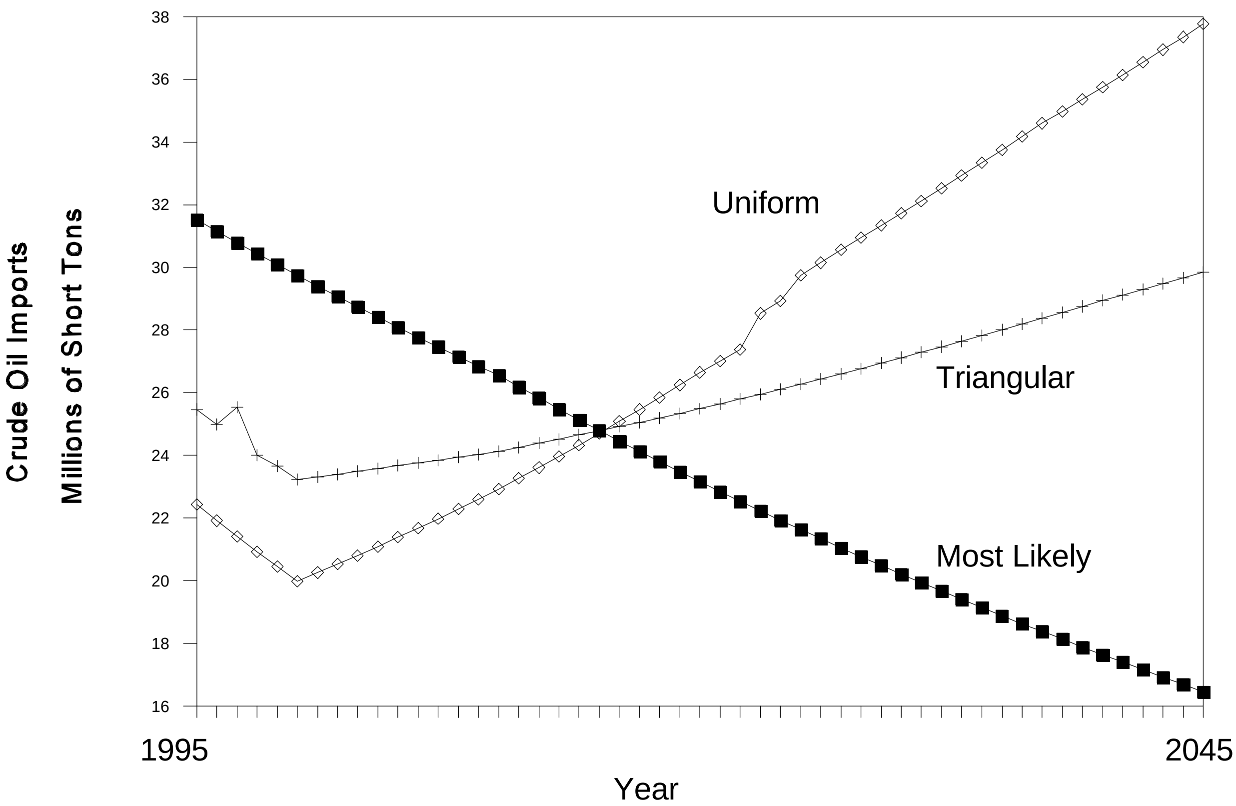


Figure 11: Most Likely and Simulation Mean Forecasts

Figure 11 compares a plot of the most likely tonnage forecast with the mean forecasts from each of the two simulations. The most likely forecast shows a steady decline in crude oil imports. The simulation results, which use data from a number of forecasts, show initial declines followed by increases. The uniform distribution dips further and rises higher than does the triangular distribution.

The patterns of these forecasts have important implications for project benefits. If the tonnages shown in the figure are to move more efficiently on larger ships as a result of the project, the simulation results clearly increase benefits in the out-years of the project, while the most likely scenario emphasizes benefits in the first couple decades of project life.

The most important point to take from this analysis is that the "most likely" scenario is not "the only" scenario. If there is more than one credible future tonnage forecast scenario, it should be considered. The information contained in that scenario should be preserved in an appropriate manner.

The simulation results, in essence, allow the analyst to say that we have gathered a number of credible forecasts prepared by experts. And, though we do not know what the future tonnage will be, it is our judgment that the tonnage will be no less than "x" tons, no more than "z" tons and it will most likely be "y" tons. It is not necessary to pick one forecast from among many and

Vessel Draft	1,000s DWT	Percent
<35'	5,472	2.1
36-40	39,756	14.9
41-48	54,491	20.4
49-60	42,318	15.9
61-70	78,044	29.2
>71'	46,535	17.5

Table 3: Future Crude Oil Foreign Flag Fleet Forecast - 1995

elevate it to special significance as the one-and-only best estimate of future conditions. It is significant to note that such a judgment by the analyst is a very realistic way of preserving alternative future condition scenarios.[6]

Uncertainty in an analysis can rapidly become compounded, often unpredictably. Deep draft navigation studies require forecasts of future fleet composition that carry the forecast commodity tonnages. Like the commodity forecasts discussed above, fleet forecasts are equally uncertain. Fleet forecasts in this case have been handled in a similar manner. The best forecast of future fleet composition is considered the most likely, but not the only, future scenario.

Table 3 presents a typical fleet forecast. The most probable future fleet is under the heading of "1000s Deadweight Tons (DWT)." A distribution of possible DWT values by draft was used instead of the single value. The 1995 crude oil fleet distribution forecasts were assumed to be normally distributed with a coefficient of variation of 0.2.[7] Thus, the values in Table 3 are the expected values of the assumed normal distributions with standard deviations equal to 20 percent of the mean.

A 1,000-iteration simulation of the future fleet composition was run to generate the distribution of percentages presented in Table 3, i.e., a random value was generated from each distribution for each draft category. This random value was, in turn, converted to a percentage of total forecast DWT for that iteration. The percentages had normal distributions, with the means and standard deviations shown in Table 4. These distributions of future fleet size were used to distribute forecast tonnages among vessels that could call at Star City under different channel

[6] It is not necessary that each future condition scenario be a complete soup-to-nuts description of the future. In many cases, it will be sufficient to describe alternative futures for key variables.

[7] The coefficient of variation is defined as the standard deviation divided by the mean. It can range from 0 to $+\infty$. Low values indicate relatively tight distributions; large values indicate wide distributions.

Vessel Draft	Mean Percent	Standard Deviation
<35'	2.07	0.44
36-40	14.94	2.86
41-48	20.45	3.72
49-60	15.90	3.02
61-70	29.17	4.65

Table 4: Distribution Parameters for Future Fleet Distribution Percentages

depth conditions to obtain shipping costs per ton.

FORMULATION OF ALTERNATIVE PLANS--EVALUATION

During this step, analysts use the data gathered and analyzed in earlier steps to begin to formulate plans that meet the planning objectives. Emphasis in this step is on formulating true alternative plans, screening them, and beginning to turn from assessing risk and uncertainty toward managing it.

The only way to ensure that the best plan is selected is to ensure that a full range of plans are considered, and objectively screened. This screening process should address each plan's contribution to the risk and uncertainty objectives as well as the NED and other objectives. Planners must begin to make judgments about acceptable levels of risk and uncertainty, risk transfers, risk-cost tradeoffs, etc.

Plan Formulation

Seven problems/opportunities were identified in the preliminary plan formulation process. They were:

1) Safety,
2) Delays,
3) Traffic congestion,
4) Loss of competitive advantage,
5) Incompatible land use,
6) Environmental vulnerabilities, and
7) Channel-related erosion.

Planning objectives were formulated to address these and other concerns (e.g., the NED objective).

There was an early consensus that channel improvements were needed. Structural measures considered included:

1) **Deeper draft**

   Channel deepening is necessary to increase economic productivity and to remain competitive with other ports.

2) **Greater width**

   Wider channels are needed to provide for safer operating conditions whether the channel is deepened or not.

3) **Bend easings**

   Because the bends in the channel are more difficult to navigate than the straight reaches, they are the most dangerous parts of the existing project. Bends need to be widened or the turning radii changed.

4) **Passing zones**

   This is viewed as an interim/partial solution.

5) **Auxiliary channels**

   Shallow draft channels could be built to ease congestion in the narrow deep draft channel.

Aids to navigation were also identified as inadequate for safe navigation. Alternatives considered include:

6) **Range lights**

   Range lights are too low, too small, hard to see, and there are not enough of them; more and better lights are desired by pilots.

7) **Buoys**

   Larger and more secure buoys are needed to mark the channel.

Erosion control measures were considered to be due more to storms than ship backwash. They were considered to be of a minor, but more immediate nature, and were handled under the Section 14 continuing authority program.

Nonstructural measures were broadly separated into navigation and landside measures. The navigation measures included:

8) **Navigation guidelines**

Specification of vessel size limits and operating restrictions for various reaches of the channel is needed.

9) **Bridge-to-bridge communications**

Formalization of the currently informal radio communication that is used to arrange meetings, passes, and overtakings is needed.

10) **Vessel Traffic Service**

An adjunct to bridge-to-bridge communications VTS would communicate with and monitor all traffic, providing information on traffic, weather, and other conditions. VTS would have the authority to direct traffic in special circumstances.

11) **Recreational boating licenses**

Annual licenses would be required for operation of any craft with 10 hp or more on board in the project area. Successful completion of a navigation safety course would be required to obtain the initial license.

The landside measures would include:

12) **Moratorium on new marinas**

No new marinas would be permitted in the project area.

13) **Comprehensive port development plan**

SCPA would develop a plan that addresses future development of the port and dredged material disposal needs.

14) **Land use plan**

Local governments bordering the project area would be required to develop zoning and land use plans consistent with the SCPA's port plan.

15) **Condemnation of existing incompatible waterfront land uses**

The array of alternatives includes several that are not typically considered part of the Corps' arsenal of alternatives. The age of the non-Federal partner, however, opens the gate to consider such measures as a serious component of any plan. To the extent that such measures have the potential to reduce project costs, they could be very attractive to local interests.

Considering a full range of alternatives is more good planning than anything else.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Depth	0	0	+	+	0	?	-
Width	+	+	+	+	0	?	?
Bends	+	+	0	+	0	0	0
Pass Zones	+	+	+	0	0	?	0
Auxiliary Channel	+	+	+	0	0	?	0
Range Lights	+	0	0	0	0	0	0
Buoys	+	0	0	0	0	0	0
Navigation Guides	+	-	0	?	0	0	0
Br-to br com.	+	0	0	0	0	0	0
VTS	+	?	0	0	0	0	0
Licensing	+	0	0	0	0	0	0
Moratorium	+	0	+	0	+	?	0
Port plan	0	?	0	+	+	?	0
Land use	0	0	?	+	+	?	0
Condemnation	0	0	+	0	+	+	0

Table 5: Preliminary Evaluation of Problems and Measures

Considering more alternatives does, however, reduce the uncertainty about having the best plan at the end of the planning process.

Screening

Table 5 presents the preliminary evaluation of each of the measures as they might contribute to the solution of an identified problem. Each measure's contribution is indicated by the symbol "+", "-", "?", or "0", depending on whether the measure makes a positive, negative, uncertain or no contribution to the problem's solution. The numbers of the problems correspond to those in the preceding section on formulation.

Screenings, such as that in Table 5, are standard fare in Corps' reports. One subtle change is the use of a "?" symbol. Rather than a "+/-" that implies the result could go either way, a "?" says that not only could the impact go either way, but we also don't know what the impact will be. The critical point for risk and uncertainty analysis is what is done about the question marks. The "?" singles out this relationship as one that needs particular attention throughout the remainder of the study. It marks an unknown that must be clarified and understood before the plans can be properly evaluated and analyzed.

It is worth noting that a "?" should not, of necessity, have a negative connotation. For example, a moratorium on marinas will have an unknown effect on environmentally vulnerable areas. The mere prevention of additional marinas eliminates the environmental disruption associated with construction of a marina. Fewer marinas means less pollution by marina users, i.e., fewer gas leaks, privy discharges, overboard wastes, etc.

Likewise, it is worth noting that a "+" or "-" does not imply a determinant relationship. Channel width increases may have a positive impact on safety, but how much of an impact is a very significant analytical issue.

<u>Risk and Uncertainty Management</u>

For simplicity, this case study concentrates on issues common to all navigation studies, i.e., the formulation of channel depth and channel width. Eliminating alternatives during the screening stage involves many considerations, one of which is risk management.

Most experienced planners would probably agree that it seems possible to eliminate at least the condemnation option. Such an alternative would not likely pass the acceptability criterion; it is simply too controversial economically and politically. Most alternatives eliminated at this stage will be eliminated for economic, engineering, environmental or political reasons. Risk and uncertainty management is likely to be an element of most such reasoning.

At this level of generality, decisions are being made to eliminate or continue with alternatives based on less than complete information. Preliminary tradeoffs must be made. Passing zones do have the appeal of being cheap, but they result in considerably more residual risk of collisions or other incidents than other alternatives. It would be perfectly reasonable to eliminate this alternative based on the judgment that it results in an unacceptable residual risk. The decision-makers' rationale for such a risk management decision would likely be based on the opinions of pilots and the Coast Guard.

Decisions like this are often made in Corps' studies. They are part of the routine, on-going risk and uncertainty management that the Corps has been practicing for years. Explicit risk and uncertainty objectives make it easier to recognize such decisions as risk management. Careful documentation of such decision processes will enhance understanding of the planning process.

The initial screening and risk management processes should help to identify significant risk and uncertainty issues to be addressed throughout the remainder of the study. In the Star City study, these issues would have to include the construction-risk cost tradeoff of the channel width question and the environmental issues related to plan formulation. In addition, to these major issues, there is a wide range of uncertainty issues generic to any navigation study. Many of these will be considered in the next section.

<u>COMPARISON OF ALTERNATIVE PLANS--DETAILED EVALUATION</u>

By this step in the planning process, the major risk and uncertainty issues should already be identified. The emphasis in this step is on assessing risk and uncertainty in specific terms. The critical risk and uncertainty analysis elements in this step include:

1) Evaluation of each alternative's contribution to the planning objectives.

2) Consciously avoiding the appearance of certainty.
3) Transition in focus to implementation issues.

Evaluation of Alternatives

While the evaluation of all plan effects is important in a study, the evaluation of project cost and benefits is the mainstay of every Corps' study. Thus, the emphasis in this section is on the risk and uncertainty elements of project economics. To keep the analysis from becoming too complicated, the evaluation in this section is limited to the consideration of channel depth. Three alternatives are considered: 45, 50 and 55-foot deep channels. Subsequent sections will return to the analysis of other specific risk and uncertainty issues.

Project Costs

Extensive engineering analyses are undertaken in a deep draft study to ascertain the effort necessary to construct the project. The project cost estimate is the single most important summary of that analysis. While economic feasibility (i.e., BCR $\geq$ 1) is required for Federal participation in a project, project costs remain the "bottom line" for many non-Federal partners.

Much of the analyses conducted during the course of a study are fraught with uncertainties of many kinds. Project costs are based largely on the quantity and quality of dredge material to be removed and the manner in which it will be disposed. Bathymetric surveys, channel geometry, overdepth dredging estimates, and scores of other analyses are conducted under less than ideal conditions. As a result, many of the countless pieces that comprise a cost estimate are uncertain values. Table 6 presents a typical summary cost estimate for the 50-foot channel project.

Now, consider the cost estimate for the 45-foot project. The best estimate of project costs is $24.2 million. This estimate is contingent upon all the analytical uncertainty (theory, model, and measurement) that has gone into the preparation of the cost estimate.

To account for the uncertainty inherent in the quantity estimates and unit prices, these values are allowed to vary according to assumed distributions.[8] Quantity estimates and lump sum

---

[8] There are other, perhaps more efficient, ways to account for the uncertainty inherent in the technical analyses that support the cost estimates. Rather than vary quantities or prices, as is done here, the analysts could vary selected key parameters or variables in the critical studies. For example, if side slopes of 2-on-1 are used for design, and the dredge material turns out to be softer than expected, side slopes of 3-on-1 may be necessary. Over the length of a project, this can be a significant additional cost. Side slopes may be varied across a minimum/maximum range to determine a range of quantities for this parameter. Similar sensitivity analysis for other key parameters or variables can be used to construct confidence intervals for any quantity estimate.

Going in the direction of less analysis, perhaps as may be necessary for retroactively doing risk and uncertainty analysis for completed or nearly completed studies, values can be adjusted by a percentage. In some cases, using professional judgment to estimate the actual range of values about a best estimate may be the most appropriate or the only option. In such a case, it is not necessary that costs are assumed to have a triangular distribution; unit prices are assumed to have a uniform

	Estimated Quantity	Unit	Unit Price	Estimated Cost
A. CHANNELS - NEW				
(1) Entrance	2,980,000	CY	$.05	$ 7,450,000
(2) Outer Bar	7,830,333	CY	2.5	19,575,833
(3) Inner Bar	1,828,000	CY	2.5	4,570,000
(4) Harper's Channel	434,333	CY	1.5	651,500
(5) Star City Channel	8,093,333	CY	1.5	12,140,000
SUBTOTAL				44,387,333
(6) Mob and Demob		JOB	LS	200,000
(7) Contingencies	20%			8,877,467
SUBTOTAL				9,077,467
(8) E&D				317,711
(9) S&A				476,567
SUBTOTAL				794,278
TOTAL NEW WORK:				54,259,078
B. CHANNELS - ADD'L				
(1) Existing Channel	2,173,333	CY	2.0	4,346,667
(2) Contingencies	20%			869,333
TOTAL ADD'L WORK:				5,216,000
C. AIDS TO NAV.				44,000
D. DISPOSAL AREAS				
(1) Liver-Smith Island	336,333	CY	4.0	1,345,333
(2) Ft. Kiner	150,000	CY	4.0	600,000
(3) Contingencies	20%			389,067
TOTAL DISPOSAL AREA:				2,334,400
E. BERTHING AREA				
(1) Star City Docks	4,566,667	CY	1.5	6,850,000
(2) Zaxxon Oil	225,333	CY	1.5	338,000
(3) Contingencies	20%			1,437,600
TOTAL BERTHING AREA:				8,625,600
TOTAL PROJECT COSTS:				70,479,078

Table 6: Star City 50-Foot Channel Cost Estimates

the estimate be symmetrical. For example, it may be that the best professional judgment is that a quantity could be 10 percent less to 20 percent more than the best estimate.

Alternative	Expected Value	Standard Deviation	Minimum	Maximum
45-Foot Channel	$ 24,190	1,910	19,010	30,565
50-Foot Channel	70,478	3,076	60,609	81,163
55 Foot Channel	87,464	4,017	74,157	103,214

Table 7: Summary of Construction Cost Estimates

distribution. The resulting first cost of construction is itself a normally distributed random variable.

Table 7 summarizes the cost estimate distributions. The mean is the best estimate of project costs. Using the mean, standard deviation, and standard normal distribution, it is a simple matter to estimate the probability of project costs greater or less than any value. For example, there is a 0.0032 chance the cost of the 45-foot project will be 20 percent or more higher (i.e., ≥ $29.03 million) than the estimated cost. There are corresponding 0.0000 and 0.0159 chances that the 50- and 55-foot project costs will actually be 20 percent greater than the estimated cost, based on the assumptions of the analysts. In this case, there appears to be little danger that any alternative will violate the 1986 Water Resource Development Act's 20 percent cap on cost overruns.

The 90 percent confidence intervals for the 45-, 50-, and 55-foot projects are 21.2 to 27.4 million, $65.5 to 75.5 million, and $81.0 to 94.1 million, respectively.[9]

The coefficients of variation, a simple measure of relative risk,[10] for the cost estimates are .08, .04, and .05 for the 45-, 50-, and 55-foot channels. This indicates relatively little deviation from the expected values, hence a relatively small chance of extremely low or extremely high costs exists. The risk of an extremely high value is twice as great with the 45-foot project as it is with the 50-foot project. In absolute terms, however, it is a small risk with either.

Project Benefits

The "Future Conditions" section addressed the considerable uncertainty inherent in forecasting future conditions. The preceding cost example has shown how cumulative

[9] For the 45-foot project, there is a 5 percent chance costs will be less than $21.2 million and a 5 percent chance costs will be more than $27.4 million. Thus, there is a 90 percent chance costs will fall between these two values.

[10] See p. F-14, Appendix F to Guidelines and Procedures for Risk and Uncertainty Analysis in Corps Civil Works Planning for an explanation of the coefficient of variation.

	Cost at Sea	Hours at	Total Sea	Full Load	Cargo	Capacity
<35'	520	122	63,375	25,000	0.95	23,750
36-40	780	122	95,063	60,000	0.95	57,000
41-45	894	122	108,956	90,000	0.94	84,600
46-50	932	122	113,588	100,000	0.94	94,000
51-55	968	122	117,975	120,000	0.94	112,800
56-60	1,063	122	129,553	150,000	0.94	141,000
61-70	1,297	130	168,610	210,000	0.91	191,100
>70	1,644	130	213,720	325,000	0.91	295,750
	Cargo per Foot	Loaded Cargo	Cost in Port	Hours to Unload	Tot. Port Cost	Tot. Cost per Ton
<35'	1,156	22,594	395	18	7,140	312
36-40	1,882	55,118	588	26	15,124	200
41-45	2,822	81,778	644	27	17,555	155
46-50	3,011	90,989	665	30	19,968	147
51-55	3,185	109,615	697	33	22,920	129
56-60	3,817	137,183	747	33	24,594	112
61-70	4,637	186,463	882	40	35,242	109
>70	5,779	289,970	1,127	48	54,299	92

Table 8: Total Cost Per Ton

uncertainties in components of an analysis (quantities and costs) yield results that are uncertain. Benefit estimates are among the most uncertain of all values because of their reliance on future forecasts and the complex web of cumulative uncertainties.

Navigation benefits for this hypothetical project are primarily transportation cost savings that are derived from using larger vessels with deeper drafts and lower average costs.[11] To estimate these benefits, shipping costs for 40-, 45-, 50- and 55-foot channel depths must be estimated. This is done by finding the cost of shipping crude oil in various size vessels, then constructing weighted averages (the weights being the estimated probabilities of ships of varying sizes carrying the oil) of shipping costs per ton of crude oil for each channel depth. These unit

[11] The case study is a much simplified representation of an actual study. Methods of shipment such as light-loading, trans-shipping, etc., are not explicitly considered in favor of a straightforward presentation that uses a different fleet mix with and without the project. The techniques demonstrated in this example are equally adaptable to light-loading, trans-shipping, and related benefit categories.

40-Foot Project	Expected Value	Standard Deviation	Minimum	Maximum
North	1.59	0.23	0.82	2.36
South	5.72	0.93	2.74	8.78
East	2.14	0.32	1.23	3.11
West	6.19	1.00	3.24	9.32
45-Foot Project				
North	1.39	0.15	0.82	1.84
South	4.89	0.62	3.03	6.98
East	1.84	0.22	1.17	2.43
West	5.30	0.67	3.20	7.56
50-Foot Project				
North	1.30	0.13	0.88	1.62
South	4.58	0.51	3.34	6.53
East	1.72	0.18	1.23	2.22
West	4.96	0.54	3.32	6.79
55-Foot Project				
North	1.11	0.10	0.79	1.39
South	3.85	0.42	2.65	5.30
East	1.46	0.14	1.05	1.94
West	4.16	0.46	2.19	5.68

Table 9: Weighted Average Transportation Cost/Ton

costs are then used to estimate the costs of moving the tonnages forecast over a fifty-year period under different channel depth scenarios. The least cost option is the project that yields the most benefits; benefits are the difference between without-project costs and with-project costs. Forecast tonnage is assumed to be the same with or without the project.

Table 8 summarizes a typical shipping cost computation, presenting the best estimate of each value. Cost at sea (1), cargo capacity (5), cost in port (9), and hours to unload (10) are all random variables, assumed to have distributions. A typical computation of total cost per ton is comprised as follows:

[((1) x (2)) + ((9) x (10))] / (8),

where the numbers refer to the variables in the columns of Table 8. Only hours at sea (2) is considered to be known in this example, and it can be readily varied. Loaded cargo (8) is a random variable because it depends on cargo capacity (5), which is a random variable.[12]

[12] Loaded cargo (8) is the product of full load tonnage (4) and cargo capacity (5). Cargo capacity is a random variable. Cargo per foot (7), useful in estimating benefits to light-loaded vessels, is not used directly in this example.

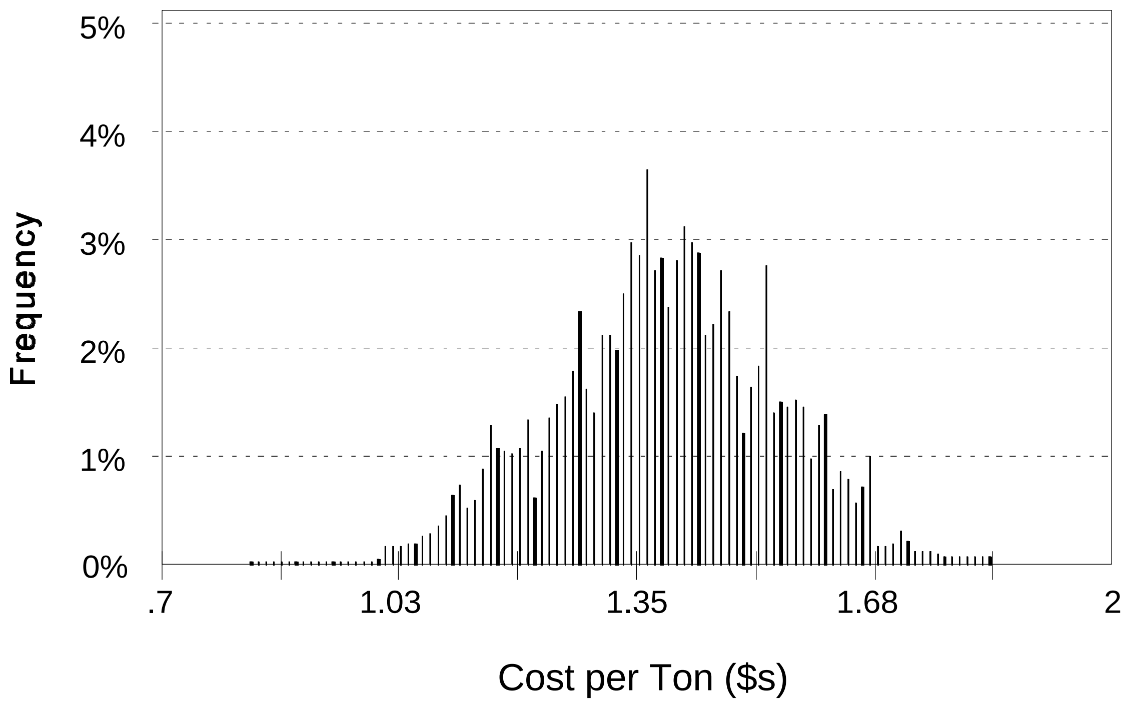


Figure 12: Transportation Costs Per Ton - Frequency Histogram

A weighted average of total costs per ton (12) was calculated for shipments from the north, south, east and west. The total cost per ton was weighted by the frequency with which vessel sizes were observed (the distribution of future fleet percentages described in Table 4). This weighted cost was computed 4,000 times using the cumulative uncertainties in fleet distribution and per ton cost estimates. The weighted average costs per ton for various channel depths are shown in Table 9. The cost estimates were normally distributed with the parameters shown. Minimum and maximum estimates are also included.

The best estimate of the cost to ship oil from the North through a 40-foot deep channel is $1.59 per ton. This estimate has taken into account the cumulative uncertainties discussed above. Analysis shows the shipping costs could be as low as $0.82 or as high as $2.36. The probability of obtaining any particular cost can be approximated with the standard normal distribution and a Z-statistic[13] using the mean and standard deviation from the table.

[13] "Z" is a normally distributed random variable with a mean of 0 and a standard deviation of 1. The variable "Z" is the standard normal random variable. Tables, available in most standard statistics texts, have been developed showing the probability of obtaining any value of the variable, Z.

These probabilities can be expressed in terms of the number of standard deviations a value is from its mean. For example, a value that is 1.64 standard deviations or more from its mean has a probability of about 5 percent of being observed.

"Z" values, or the equivalent number of standard deviations a value is from its mean, can be

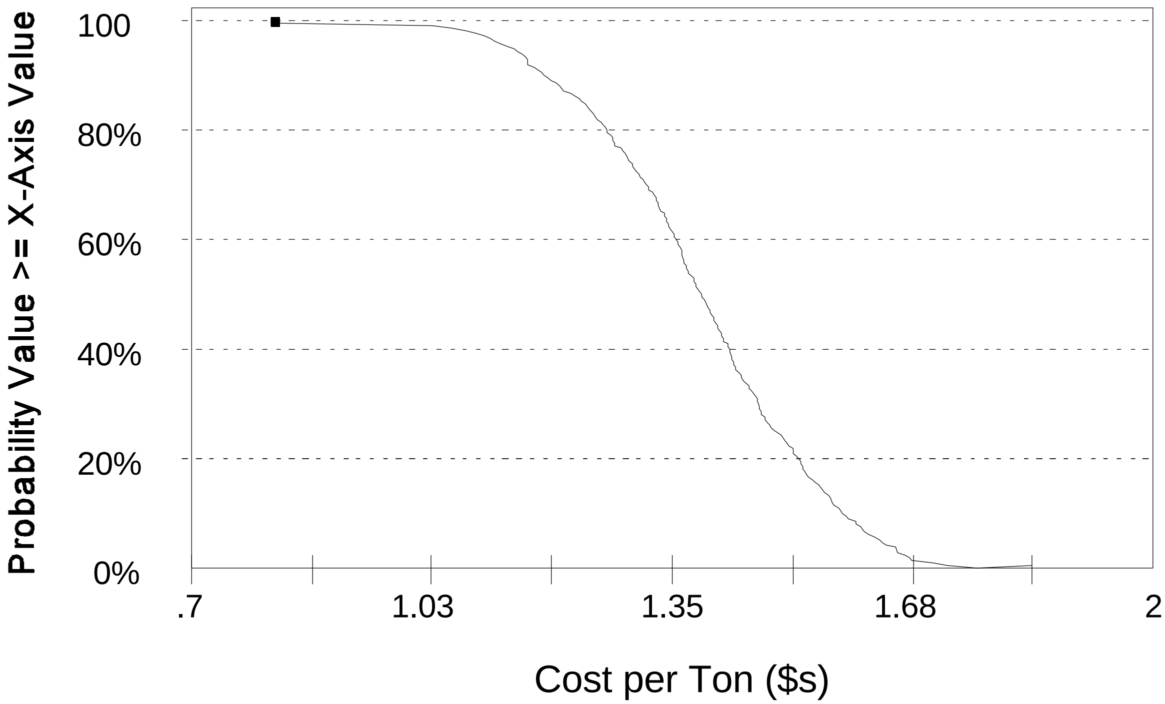


Figure 13: Transportation Costs Per Ton (45') Cumulative Distribution

Figure 12 shows the distribution of per ton transportation costs for crude oil shipped from the North through the 45-foot project. The normal distribution of cost estimates is a practical example of one of the results of the Central Limit Theorem, i.e., a random variable that is a function of many other random variables will have an approximately normal distribution regardless of the distributions of the random variables that comprise it. Figure 13 presents the same information in a cumulative distribution.

The distributions of transportation costs are used to estimate project benefits as shown in Table 10

computed for any normally distributed random variable. This conversion is given by:

$$Z = (X-\mu)/\sigma$$

where "X" is the value of the variable whose probability we want to estimate, "μ" the mean of population, and "σ" the standard deviation of the population. In the absence of population parameters, sample means, and standard deviations can be used. The resulting value is a "Z" value or "Z" statistic, whose value can now be looked up in any standard normal table.

			Shipment Distribution		
Year	Total Tons	North 36.0%	South 17.5%	East 53.5%	West 25.0%
1995	25,267	6,946	3,376	10,322	4,823
2000	23,241	6,338	3,081	9,420	4,402
2010	24,132	6,581	3,199	9,781	4,570
2020	25,455	6,942	3,375	10,317	4,821
2030	27,122	7,397	3,596	10,993	5,137
2040	28,953	7,896	3,838	11,735	5,483
2045	29,903	8,155	3,964	12,120	5,663
Depth			Transportation Cost/Ton		
45' Channel		1.59	5.72	2.14	6.19
50' Channel		1.39	4.89	1.84	5.30
55' Channel		1.30	4.58	1.72	4.96
Depth			Transportation Savings/Ton		
45' Channel		0.20	0.83	0.30	0.89
50' Channel		0.29	1.14	0.42	1.23
55' Channel		0.48	1.87	0.68	2.03
			45-Foot Channel Total Savings		
Year	Total Savings	North	South	East	West
1995	11,749	1,531	2,798	3,123	4,298
2000	10,722	1,397	2,553	2,850	3,922
2010	11,133	1,450	2,651	2,959	4,073
2020	11,744	1,530	2,796	3,121	4,296
2030	12,513	1,630	2,980	3,326	4,577
2040	13,357	1,741	3,181	3,550	4,886
2045	13,796	1,798	3,285	3,666	5,047
			Benefits		
Depth		Accumulated PW Benefits		Avg. Annual Benefits	
45' Channel		117,454		10,435	
50' Channel		163,064		14,487	
55' Channel		266,016		23,633	

Table 10: Star City Channel Project Benefits

. Total savings per ton are illustrated for the 45-foot channel depth. Other channel depths were similarly computed. Total foreign tonnage in Table 10 is allowed to vary as described in the "Future Conditions" section. The percentage of that tonnage from each origin (north, south, etc.) also varies.[14] Transportation costs per ton are taken from Table 6 and,

[14] Because the percentage of oil from any origin is allowed to vary independently from all other origins, the sum of these percentages may exceed 100. It is impossible to have more than 100 percent of all oil shipped, so these percentages are normalized. For example, if the percentages for the four

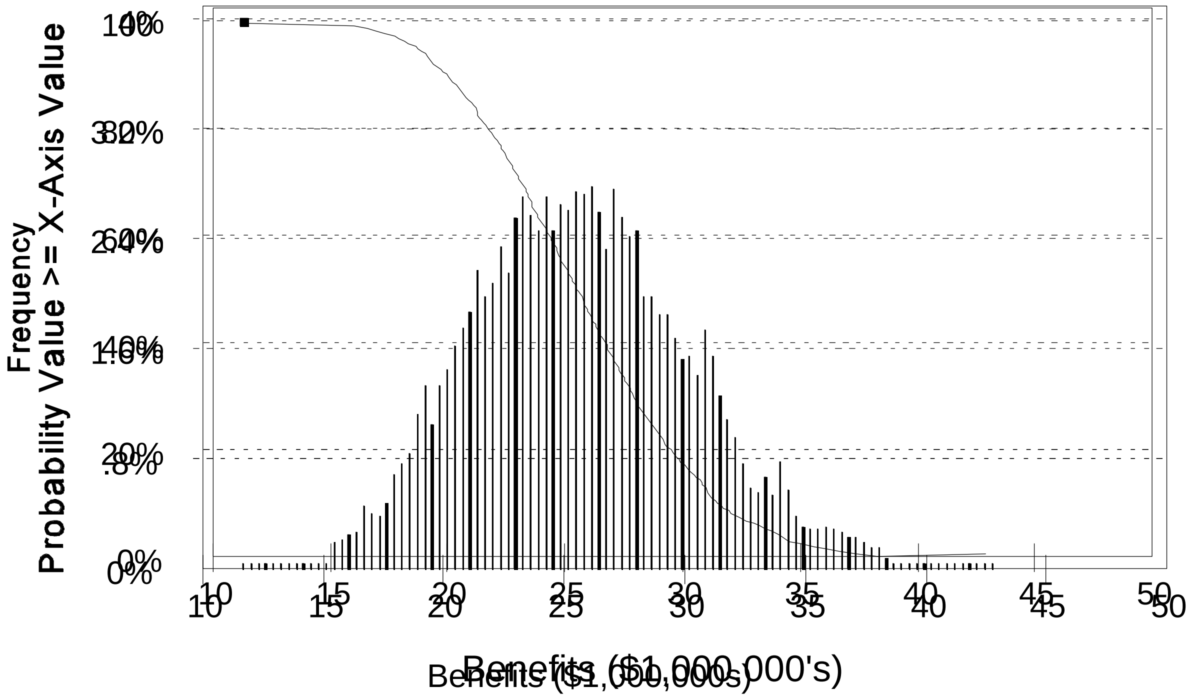


Figure 14: Expected Annual Benefits Distribution - 55' Channel

Figure 15: Project Benefits Cumulative - 55' Channel

likewise, vary. As a result, benefits are a function of varying tonnage forecasts, varying origins, varying transportation costs, and varying future fleet distributions. The analysis does not rely on the best estimate of any of these variables. Allowing these critical variables to vary is a practical way to preserve alternative future scenarios.

"Project benefits" is a random variable. Table 10 presents the single best estimate of benefits to the 55-foot project. Figures 14 and 15 show a histogram and cumulative distribution for average annual benefits for the 55-foot channel. Similar distributions exist for each channel alternative.

The best estimate of expected annual benefits for the 55-foot project is $23,636,000. However, benefits could be as high as $38.8 million or as low as $10.6 million.

Project benefits for the three channel alternatives are summarized in Table 11.

Avoiding the Appearance of Certainty

Basic costs and benefits were evaluated in the previous section. In the following section, they will be brought together in the plan formulation analysis step. Ultimately, a plan will be

---

origins were 25, 25, 50, and 50 for a total of 150 percent, each percent would be divided by 150. This would yield percentages of 17, 17, 33, and 33, respectively.

	Expected Value	Standard Deviation	Minimum	Maximum
45-Foot Channel	$ 10,435	$ 2,278	$ 3,758	$ 18,977
50-Foot Channel	14,488	3,164	4,385	26,244
55-Foot Channel	23,636	4,192	10,623	38,802

Table 11: Expected Annual Benefits ($1,000s Dollars)

selected from among the alternatives. It is essential in the decision, and even the implementation, process that decision-makers not regard project effects as known and certain events.

Decision-makers must weigh the likelihood of various outcomes in arriving at their decision. In order to convey to decision-makers and the public the fact that project effects (e.g., costs and benefits) are random variables and not certain values, it is essential that project evaluations convey this information from the outset.

The preceding discussion of costs illustrates how this can be done. Though a best estimate of costs is presented, 90 percent confidence intervals are presented along with the estimated probability of a 20 percent or greater cost overrun. Tables and figures used to summarize costs consistently stress the uncertain nature of cost estimates. In an actual study, it may be useful to present information on the uncertain nature of smaller components of the planning effort. For example, the distribution (or simply a minimum-maximum range) of dredge material quantities from, say, the Outer Bar of the Star City project, may be presented.

These and other techniques can be effectively used throughout the study process[15] for costs, benefits and any key decision variable or the theory, models or measurements that are critical to the estimation of those variable values.

In turning some attention to implementation issues in this stage of the study it is essential to stress that none of the alternatives under consideration come with guarantees. It is perhaps most appropriate that the implementation emphasis, with regard to risk and uncertainty analysis, be concentrated on educating Corps and non-Federal decision-makers about the nature and consequences of the risks and uncertainties surfaced and evaluated to this point. The education task should not be left until the end of the project.

[15] It is important to note that the study process includes far more than the documentation of the study effort in the final report. Avoiding the appearance of uncertainty needs to be done in all contacts with the public and the non-Federal partner, as well as among the study team, supervisors and throughout the Corps' own in-house planning and review processes.

COMPARISON OF ALTERNATIVES--DETAILED ANALYSIS

This step is critical in the management stage of the risk and uncertainty analysis. The cumulative impacts of risk and uncertainty on the performance of the alternatives must be summarized in a manageable and reasonably comparable way. The critical elements of the analysis at this point include:

1) Quantifying the cumulative effects of risk and uncertainty;
2) Comparing the risk and uncertainty aspects of the alternatives; and
3) Displaying the results of the analysis.

Due to the considerable overlap of these elements, they are addressed together in this example. The cumulative effects are addressed primarily in the presentation of the benefit-cost ratio. In this section, evaluations of costs and benefits are brought together, and significant decisions are made regarding alternatives to be analyzed in detail. This detailed analysis will include risk-cost tradeoffs for channel width determination.

The costs in the preceding section have been expanded to include annual operation and maintenance costs that are assumed to be random variables. Thus, annual costs include the amortized first costs of construction plus annual O&M. Benefits are as described earlier.

Looking ahead to project construction, it is possible that dredging quantities, having been conservatively estimated, are overstated in the above tables. Likewise, it is possible that at the time project contracts are bid, there may be a great deal of excess capacity in the dredging industry, resulting in lower-than-expected unit prices. These events would result in a lower-than-expected project cost.

On the benefit side, crude oil imports may be much greater than expected. More of the oil may come from the South and West, where transportation savings are greatest. The costs of shipping through the existing 40-foot project may be greater than estimated. Costs for the deep draft vessels that could call at Star City only with an improved project may not be as much as expected. These events combine to result in greater project benefits than expected. Combine them with the low cost events, and a large benefit cost ratio (BCR) may be obtained. On the other hand, events could result in higher than expected costs, low benefits and a small BCR. Project feasibility, as measured by the BCR, is a random variable.

	Expected Value	Standard Deviation	Probability BCR<1 / Probability NB<0	Minimum	Maximum
45' Channel	$37.656	$02.8239	0.00000	$1.3091	$6.91734
50' Channel	27.002	03.4473	0.00065	0(2.6891)	3.17902.14
55' Channel	19.695	04.3209	0.00055	0(2.7986)	22749.927

Table 12: Summary Description of Project BCRs / Table 13: Project Net Benefits Summary - $1,000,000's EAD

Table 12 summarizes the BCRs for the three alternatives under consideration. The 45-foot project is expected to return $3.65, in expected annual dollars, for every annual dollar invested. However, under favorable circumstances (i.e., low costs and high benefits), it could return as much as $6.97, and under unfavorable circumstances, as little as $1.31. There is virtually no chance that the 45-foot project will yield a negative return on the investment.[16] This is a very significant piece of information that is not generally available to decision-makers. You can't lose money with the 45-foot project.

The 50-foot project has a return that ranged, in our 4,000- iteration simulation, from $0.61 to $3.70. There is less than a one percent chance of a negative return on investment, however, the possibility of a negative return does indeed exist. The 55-foot project returns ranged from $0.78 to $2.80, with less than a one percent chance of an infeasible project. The results of these analyses indicate that regardless of the project chosen, there is little chance of losing money.

The 90-percent confidence interval for project BCRs are, in order: 2.35 to 5.09, 1.29 to 2.74, and 1.21 to 2.22. The 45-foot project is the best choice by the BCR criterion. The coefficients of variation are 0.23, 0.22, and 0.18, indicating more variation from the mean than the costs exhibit. The spread in results gets narrower as project size increases. Thus, if obtaining the expected value result is the goal, choosing a project with the lowest coefficient of variation is desirable.

The BCR does not, of course, tell the entire story. Maximizing net benefits is the generally-accepted economic criterion used by the Corps in project planning. Table 13 summarizes net benefits for the three alternatives. Under the net benefit criterion, the 55-foot

[16] There are two significant constraints on the credibility of such a statement: construction of the simulation model and the size of the simulation. First, if the underlying assumptions about project costs and benefits are objective and reasonable and the model is carefully constructed, then we can be confident that a realistic range of potential results has been defined. Second, if there is a large number of iterations in the simulation, we can be confident extreme value estimates of the BCR will be obtained.

project is the best choice based on expected values, with $9.65 million in expected annual net benefits.

The 55-foot project has the potential, however slight, to lose nearly $3 million in expected annual dollars. The 50-foot project has a slightly higher chance of a similar loss, but with a lower expected value. The 45-foot project offers a high expected value, with effectively a zero chance of a negative return.

The results in Table 13 present a classic risk decision. Decision-makers can select the 55-foot project, with the highest expected return and a small chance of a significant loss, or the 45-foot project, with a lower expected return and a virtually assured positive return. Is an additional $2 million annually worth the risk of a possible $3 million expected annual loss? This is a risk management problem for decision-makers, to be taken up in the plan selection process.

In a traditional Corps' analysis, the 55-foot project would be the recommended plan based on the NED criterion. The risk and uncertainty presented above indicates this is a fairly reasonable and circumspect choice. However, it is not difficult to imagine circumstances in which the alternative scenarios and additional information presented by the risk and uncertainty analysis contribute to the selection of a different plan.

Item	Rate of Occurrence*
Catastrophes	0.0005
Collisions	0.1372
Ramming Non-Navigation Aids	0.0920
Groundings and Other	0.1832
Delays	328.9000
Item	**Distribution of Damages per Event†**
Catastrophes	Triangular ($10000,$500000,$1000000)
Collisions	Trunc. Normal ($646,$100,$75,$5000)
Ramming Non-Navigation Aids	Trunc. Normal ($175,$50,$20,$1000)
Groundings and Other	Trunc. Normal ($9,$3,$0,$35)
Delays	Uniform ($1.8,$4.2)

*Rate is per 1,000 encounters.
†Damage in $1,000 per event.

Table 14: Historical Casualty and Delay Rates

Imagine, for the moment, that Star City is the non-Federal partner and has been under severe fiscal strain in recent years. It is possible that coalitions of project opponents (say, environmental interests, realtors, and recreational boaters) could mount an effective political challenge to the 55-foot project based on the argument that any increase in expenditures, particularly one with a risk of additional financial loss to the public sector, is too high. In such a decision environment, the 45-foot project may arise as the best alternative.

The above analysis identified a 55-foot channel depth as optimal.[17] The existing channel width is 400 feet, and that is clearly unacceptable to local interests. While the channel depth determination is for productivity, channel width determination is for safety and has not yet been addressed.

[17] To simplify the presentation, depths greater than 55 feet are not considered. This could be because of an underwater harbor tunnel that constrains the maximum depth or for any other number of reasons. In an actual study, if the maximum channel depth considered maximizes net benefits, it would be necessary to evaluate a deeper channel, if physically feasible, in order to assure that the most efficient channel size (i.e., maximum net benefits) has been identified.

In the Star City project, total benefits are not affected by channel width. Annual benefits accruing to the 55-foot project are expected to be $23,636,000 regardless of the channel width. With a 400-foot project, however, there would be project costs in addition to construction costs already considered. A 400-foot wide channel would require substantial delays to vessels while the large deeper draft ships attracted by the project transit the channel. The frequency of groundings, collisions, and other incidents is also likely to increase, even without larger vessels, due to increased tonnage in the future. These problems are expected to only get worse with larger vessels and the same width project.

Project safety has not been considered previously, so that it may be considered in its entirety here. Clearly, project safety is a key variable that would be considered early and throughout the project, as indeed it was identified as a major problem for the Star City project.

"Casualties" are defined as collisions between moving vessels, ramming of non-navigation aids (e.g., moored vessels, piers, etc.), groundings and other incidents (e.g., ramming of navigation aids). "Delays" are also considered as risk costs in this discussion, but they are not casualties. In the channel width discussion, "risky events" are defined as casualties and delays.

Delays result when the combined beam width of two vessels meeting (i.e., passing in opposite directions) or overtaking (i.e., passing in the same direction) in the channel exceed the channel width design criteria established by the Corps.

Forecasts of risky events are based on historical casualty and delay rates from the period of available data, 1978 through 1989. The observed distributions of collisions, ramming, grounding and other, and delays per 1,000 encounters (or opportunities for events) over this period are shown in Table 14. Using these rates and the distribution of future tonnage projections, casualties and delays were forecast, along with the expected damages associated with each.

"Catastrophes" in this context, are considered to be rare events with extremely adverse environmental consequences.[18] They are characterized by small probabilities of occurrence and large consequences. This category includes the environmental disasters that result from large oil spills, liquefied natural gas disasters, etc.

Tonnage forecasts, consistent with those described earlier, were generated. From these distributions, numbers of encounters between ships, ships and tows, and tows were estimated. These encounters included all project area traffic, not just crude oil vessels.

An estimated incident rate per 1,000 encounters was generated from distributions with the

[18] The range of environmental consequences of catastrophic casualties is so broad as to merit its own risk and uncertainty analysis. For simplicity, we avoid specific description and analysis of the nature of the catastrophe and merely estimate the range of damages that result from it. Estimating these dollar damages is itself a topic worthy of its own case study.

	Mean	Minimum	Maximum	Standard Deviation
Present Worth				
Costs w/40'	$ 90,727	$ 21,049	$ 217,066	$ 32,660
Costs w/55'	58,446	15,737	164,276	22,459
Cost Reductions	32,280	0	163,367	38,637
Expected Annual				
Costs w/40'	8,060	1,870	19,284	2,902
Costs w/55'	5,192	1,398	14,594	1,995
Cost Reductions	2,868	0	14,514	5,432

Table 15: Risk-Cost Benefits Due to Channel Deepening ($1,000's)

mean rates shown in Table 14. Multiplying the probability of casualty/delay times the number of ship-to-ship encounters[19] yields the number of casualties of that type or delays that occur in a given year (i.e., one iteration). The mean damages of those events were generated from distributions also shown in Table 14.[20] The product of the mean damage and the number of events yield total damage for the year. Casualty damages and delay costs for the year were summed, and the present worth and expected annual values were calculated for a 50-year planning horizon.[21]

These calculations were repeated 4,000 times for the 40-foot and the 55-foot projects.

[19] To keep the case study simple, the safety analysis considers only ship-to-ship encounters. It is a straightforward adaptation of the method described here to extend the analysis to ship-to-tow or tow-to-tow encounters.

[20] Parameters for each distribution follow in parentheses. The triangular distribution lists the minimum, most likely and maximum value. Truncated normal distribution parameters are, in order, the mean, standard deviation, minimum and maximum values. Minimum and maximum values are provided for the uniform distribution.

[21] The approach used here is a relatively simple expansion of an approach actually applied in a recent Corps' study. The approach was expanded to demonstrate the ease with which uncertainty can be incorporated into an analysis. The channel width determination analysis presented here is but one of many reasonable approaches to the problem. For an example of an alternative approach, see "The Construction Cost/Risk Cost Trade-Off in Public Works Projects: Navigation Channel Width Determination" by Charles Yoe in Risk Analysis and Management of Natural and Man-Made Hazards, Haimes and Stakhiv, editors, ASCE, New York 1989.

Channel Width:	Expert Opinion Reduction:
400'	0% (Base Line)
500'	40%
600'	55%
700'	67%
800'	78%
900'	90%
1000'	92%

Table 16: Expected Casualty and Delay Reductions

The differences between the casualty and delay costs for the 40- and 55-foot projects are safety benefits that result simply because the deeper project results in larger cargoes and hence, fewer vessels, fewer ship-to-ship encounters, and fewer casualties and delays. Thus, deepening the project reduces the risk casualties by decreasing traffic.[22] Table 15 summarizes these benefits.

Risk and casualty damage reductions are expected to be $2.9 million in expected annual dollars, but they may be as high as $14.5 million or they could actually increase in rare instances.[23] Although deepening the channel contributes significantly to the solution of the existing safety problem, channel widening was a major concern of the local interests. The damages and damage reductions described above are based on a 400-foot wide 55-foot deep channel. A wider channel would presumably result in further reductions in casualty and delay costs.

A major difficulty in this analysis was the quantification of the reduction in casualty and delay events that are attributable to increased channel widths. It was the analysts' judgment that such reductions could best be estimated by drawing on the experience and judgment of experts. Representatives of the pilots, towing companies, the Coast Guard, the Corps, the National Science Foundation, and the port authority agreed to serve on a delphi panel to estimate these

[22] While the number of encounters decreased as a result of fewer encounters, it is likely that the damage distributions would change. It is likely that the mean and standard deviation would be larger with larger vessels. The larger vessels and their cargoes imply potential for greater damages resulting from most catastrophes and delays. These changes in damage distributions were not incorporated in the current instance.

[23] Evaluations of the risk/delay costs for the 40-foot and 55-foot channels, when treated as independent of each other, can result in increased damages for the deeper project. While unlikely, there are enough variables unaccounted for in the analysis that this outcome is possible. The model was not constructed to preclude this possibility.

reductions.

Each of the experts was asked to estimate the percentage reduction in specific casualty and delay events in various areas of the project that would result from different project widths. Estimates were prepared individually, without discussion with or knowledge of the other experts. There was considerable variation in the responses obtained. The anonymous results and rationales offered were summarized and recirculated to the panel of experts, who were asked to revise their opinions if desired.

After three such rounds, a clear consensus was reached. At that point, the experts were brought together for the first time to examine and discuss the consensus they had independently reached. Table 16 presents the consensus risk and delay cost reductions for the different channel widths.

Figure 16 provides a visual summary of the risk-construction tradeoff inherent in the channel width selection. Wider channels cost more to construct because of the greater dredging and disposal requirements. Wider channels are also safer, with less risk of casualties or delay. The right-hand side of the figure presents the same information in terms of marginal benefits and costs.

Given that project navigation benefits are the same for any channel width, the formulation issue, from an economic perspective, is to choose the width that minimizes the cost of providing those benefits; that is, the width that minimizes the sum of construction and risk costs. In Figure 16, "Total Costs" are the vertical sum of "Construction and Risk Costs." Costs are measured in accumulated present worth dollars to make the trade off between construction costs[24] and risk costs more apparent. Project benefits from transportation cost savings are more than sufficient to support the costs of any of the channel width alternatives.

Table 17 summarizes the marginal risk cost reductions and marginal construction cost increases for the different channel widths under the most probable future scenario. Risk cost reductions are the marginal benefits (MB), construction costs are the marginal costs (MC). Optimal channel size is obtained where net benefits are maximized, i.e., MB = MC. At channel widths of 500 feet and below, marginal net benefits are positive (MB > MC). At channel widths of 600 feet and more, marginal net benefits are negative (MB < MC).

[24] The accumulated present worth of project costs are life cycle costs, i.e., they include the accumulated present worth of annual operation and maintenance costs as well. First costs of construction starting with the 400-foot channel shown in Table 17 are $87.5, $102.9, $123.0, $143.1, $163.2, $183.3, and $203.5 million, respectively. The difference between these values and those shown in the table is due to capitalized annual costs.

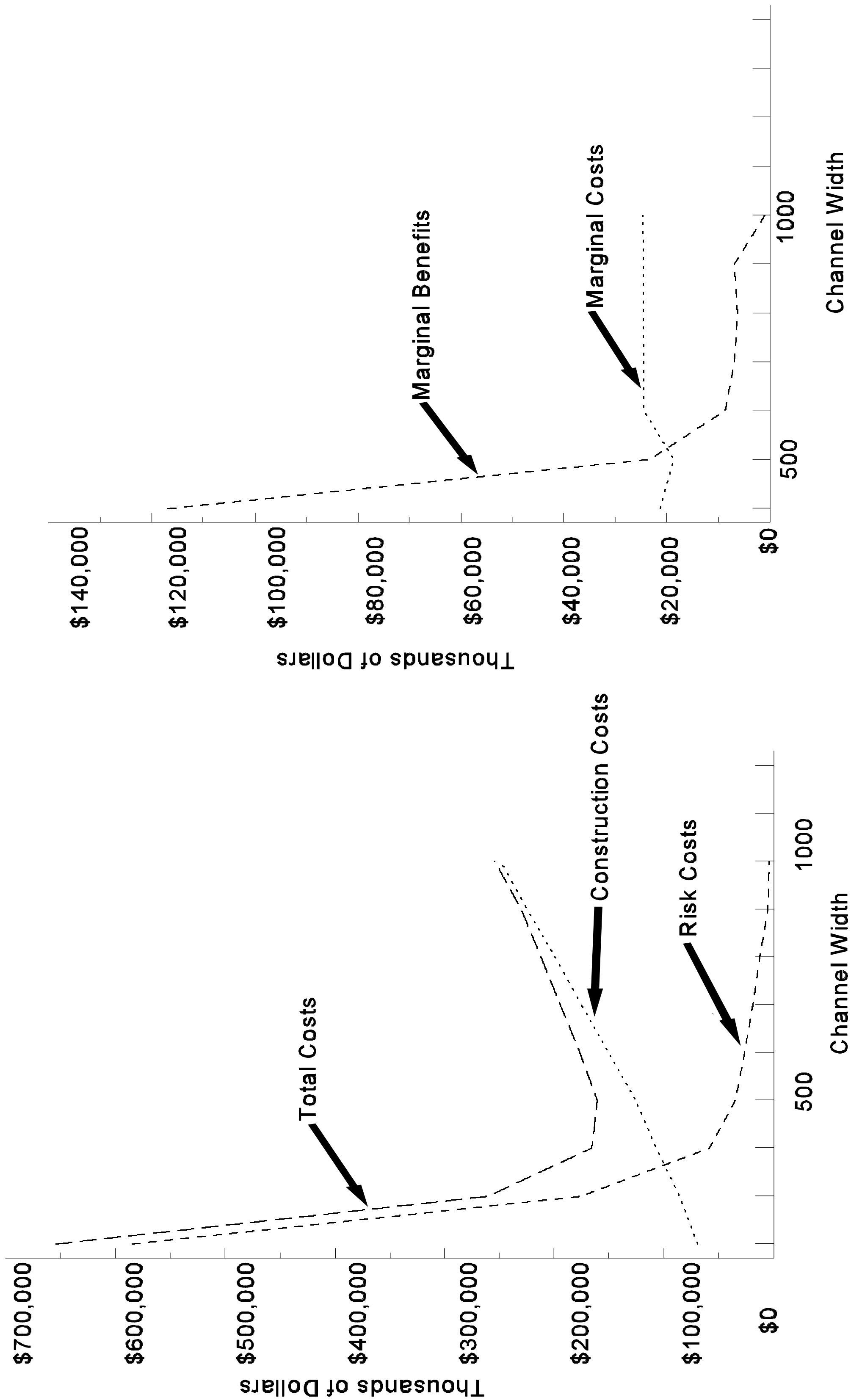


Figure 16: Risk-Construction Cost Tradeoff

	PW 55' Damages	PW Project Costs	Total Costs	Marginal Benefits	Marginal Costs	Marginal Net Benefits
0'	2,000,000	0	2,000,000			
100'	1,800,000	48,150	1,848,150	200,000	48,150	151,850
200'	584,770	69,550	654,320	1,215,230	21,400	1,193,830
300'	175,431	85,600	261,031	409,339	16,050	393,289
400'	58,477	107,000	165,477	116,954	21,400	95,554
500'	35,068	125,893	160,961	23,409	18,893	4,516
600'	26,301	150,465	176,766	8,767	24,572	(15,805)
700'	19,288	175,054	194,342	7,013	24,589	(17,576)
800'	12,858	199,670	212,528	6,430	24,616	(18,186)
900'	5,845	224,296	230,141	7,013	24,626	(17,613)
1000'	4,676	249,019	243,695	1,169	24,723	(23,554)

Table 17: Risk/Construction Cost Tradeoff Most Probable Future ($1,000's)

Thus, net benefits are maximized at a channel width of about 500 feet.[25, 26]

Choosing a channel width purely on the basis of economic criteria would result in a channel width of 500 feet, likely still too narrow in the view of local interests. The results of the

[25] The marginal analysis presented here uses discrete marginal values, sometimes called "incremental values." There is a trick to interpreting a discrete marginal value. Common sense tells us that $7,941,000 is the net marginal value of a 500-foot channel. A marginal value is simply the slope of its parent total curve. Marginal net benefits are the slope of the total net benefits curve.

The slope of this curve at 400 and 500 feet, respectively, will not be $7,941,000. This value is really a kind of average. It is the slope of a straight line that connects the two channel widths, and thus is more the slope of the curve at its midpoint. Thus, the $7,941,000 is more the slope of a point midway in the range for which it is computed, or 450 feet.

Using this "midpoint rule" for discrete marginal values, we see that marginal net benefits are negative at about 550 and are positive at 450. It is not unreasonable to assume that benefits are zero at about 500 feet. Thus, the interpretation offered in the text produces a reasonable result despite the less than rigorous use of the discrete marginal value.

[26] In actual studies, it may be advisable to look at smaller channel width increments than are considered here.

risk and uncertainty analysis lend themselves to analyzing alternative scenarios.

Table 18 presents an alternative to the most probable future scenario. The maximumvalue for damages generated during the casualty/delay analysis is used to identify a worst-case scenario. Under the worst-case scenario, we find the optimal channel width is now 600 feet.

Risk and uncertainty analyses have provided us with a scenario that indicates that a channel 100 feet wider than the existing channel is optimal. A worst-case analysis suggests an additional 100 feet in width is justified. What is the likelihood that a worst-case scenario will be obtained? It is the probability that risk costs will be at least $164,276,000[27] for a 400-foot channel or about 1-in-4,000. That, however, is not the only scenario under which the 600-foot width is optimal.

Using the percentage reductions generated by the panel of experts, any risk cost equal to or greater than $134,000,000 over the course of the project life would indicate an optimal channel size of 600 feet.[28] The results of the channel width risk cost analysis indicate there is a 0.0046 chance of costs this magnitude or greater. Thus, there is a 0.0046 chance the true optimal channel width is 600 feet.

The percentage reduction estimated by the experts is, potentially, a critical variable that arises late in the formulation process. By its very nature, it is clearly a variable that can never be known with certainty. Project formulation sensitivity to this variable can be tested by a traditional sensitivity analysis. To illustrate this approach, the experts' estimates are increased and decreased in increments of 10 percent to a maximum of 50 percent. The results of this sensitivity are shown in Table 19, parts (A) and (B).

If damage reductions are 10 percent less than the experts expect, the optimal channel width is 500 feet. This is due to the marginal benefit curve. For all other reductions, the 400-foot channel is optimal.

If expected damage reductions estimates are too low and are allowed to increase by up to 50 percent, the optimal channel size is still 500 feet.

---

[27] $164.3 million represents the worst case risk and delay cost scenario. These are the risk costs with a 400-foot channel. Additional channel widths reduce this amount by some percentage. Under this scenario, a 600-foot channel is justified. The probability that a 600-foot channel is optimal is roughly the probability that $164.3 million in damages occurs. As will be shown, the 600-foot channel may be optimal for damage levels less than $164.3 million. If so, the probability of a 600-foot optimal channel width will change.

[28] To see this is so, substitute $134 million into the PW 55-foot Damages for a 400' channel in Table 17 and recompute the table values. The $134 million is reduced by the percentages presented in Table 16 to do this.

	PW 55' Damages	PW Project Costs	Total Costs	Marginal Benefits	Marginal Costs	Marginal Net Benefits
0'	2,000,000	0	2,000,000			
100'	1,800,000	48,150	1,848,150	200,000	48,150	151,850
200'	1,643,000	69,550	1,712,550	157,000	21,400	135,600
300'	492,900	85,600	578,500	1,150,000	16,050	1,134,050
400'	164,300	107,000	271,300	328,600	21,400	307,200
500'	98,580	125,893	224,473	65,720	18,893	46,827
600'	73,935	150,465	224,473	24,645	24,572	73
700'	54,219	175,054	229,273	19,716	24,589	(4,873)
800'	36,146	199,670	235,816	18,073	24,616	(6,543)
900'	16,430	224,296	240,726	19,716	24,626	(4,910)
1000'	13,144	249,019	262,163	3,286	24,723	(21,437)

Table 18: Risk/Construction Cost Tradeoff Worst Case Scenario ($1,000's)

It is clear from this analysis that if the experts overestimated the damage reductions, plan formulation could be significantly affected. A ±10 percent assumption could yield anything from 400 to 500 feet. Incorporating these results in the decision process is addressed in the Plan Selection Section.

Simulation provides an alternative to this approach. Using the same ± 50 percent bands, a 4,000-iteration simulation was run using the same model described above. Table 20 presents the results of the simulation.

The simulation assumed the reduction percentages varied according to triangular distributions. The most likely values were taken from Table 16. Minimum values were 50 percent less and 50 percent more, to a maximum of one, of these most likely values. The results show that a 500-foot channel is the optimal size. There is an 81 percent chance the risk/construction cost tradeoff will yield positive net marginal benefits. These net marginal benefits we have been discussing should not be confused with net project benefits, a subject taken up in the next section.

Prior to the project analyses, local interests favored channel widths approaching 1,000 feet. The casualty/delay analysis shows that deepening the channel has a significant effect on lessening the risks of future casualties and delays. Because the tonnage moved through the harbor

(A)

	10% Reduction	20% Reduction	30% Reduction	40% Reduction	50% Reduction
400'	95,554	95,554	95,554	95,554	95,554
500'	2,159	(180)	(2,519)	(4,859)	(7,198)
600'	(16,678)	(17,555)	(18,432)	(19,309)	(20,186)
700'	(18,273)	(18,975)	(19,677)	(20,379)	(21,080)
800'	(18,827)	(19,470)	(20,113)	(20,757)	(21,400)
900'	(18,310)	(19,012)	(19,714)	(20,416)	(21,117)
1000'	(23,670)	(23,787)	(23,904)	(24,021)	(24,138)

(B)

	10% Increase	20% Increase	30% Increase	40% Increase	50% Increase
400'	95,554	95,554	95,554	95,554	95,554
500'	6,837	9,176	11,515	13,854	16,193
600'	(14,923)	(14,046)	(13,169)	(12,292)	(11,415)
700'	(16,870)	(16,168)	(15,467)	(14,765)	(14,356)
800'	(17,540)	(16,897)	(17,072)	(20,990)	(24,616)
900'	(16,907)	(20,883)	(24,626)	(24,626)	(24,626)
1000'	(24,138)	(24,723)	(24,723)	(24,723)	(24,723)

Table 19: Risk/Construction Tradeoff Sensitivity Analysis ($1,000s)

is expected to be the same with or without a deeper channel, larger vessels mean fewer vessels are required to move the cargo. Fewer vessels means fewer transits and encounters and, ultimately, fewer casualties and delays.

The present worth of risk cost reductions, due to the reduced traffic (deeper channel), is estimated to be $32,280,000. The existing channel width and depth result in estimated accumulated risk costs of $90,727,000. Deepening the project reduces these costs by 36 percent. Widening the project to 500 feet further reduces risk costs another $23,409,000, to a total of $35,038,000. Deepening the channel to 55 feet and widening it to 500 feet reduce existing risk costs by 61 percent overall. Extension of the channel width beyond 500 feet is not expected to be

	Net Marginal Benefit Mean	Net Marginal Benefit Minimum	Net Marginal Benefit Maximum	Net Marginal Benefit Probability > 0
500'	4,498	(6,953)	15,994	0.8197
600'	(15,028)	(24,563)	9,803	0.0217
700'	(16,228)	(24,585)	13,081	0.0272
800'	(19,100)	(24,606)	3,557	0.0042
900'	(20,933)	(24,609)	536	0.0002
1000'	(22,742)	(24,720)	(2,919)	0.0000

Table 20: Risk/Construction Cost Tradeoff Variable Damage Reductions Simulation ($1,000's)

economically justified under the most probable future scenario.

PLAN SELECTION

At this point in the planning process, risk and uncertainty assessment is essentially complete. Emphasis turns to risk and uncertainty management.

The detailed analysis and evaluation show that a 55-foot project depth is optimal. Following identification of the optimal depth, the major formulation effort was to determine the optimal project width. Table 21 summarizes the economics of the 55-foot alternatives. Under the most likely future scenario, the 500-foot wide, 55-foot deep channel maximizes expected annual net benefits at $20.3 million and is the NED plan. Figure 17 summarizes total benefits, costs and net benefits for the 55-foot alternatives.

Transportation cost savings and benefits, due to lessened traffic as a result of the deeper project (Depth Safety Benefits), are the same for each alternative. Thus, economic optimization depends solely on the marginal benefits of wider channels compared to the marginal costs of the wider channels, as presented earlier.

The NED plan has effectively no chance of having a benefit cost ratio less than 1. The minimum BCR estimated in a 4,000-iteration simulation varying all the values in Table 21 simultaneously was 1.28. The maximum BCR was 4.42. The expected value of the BCR is 2.86. Figures 18(A) and 18(B) summarize the distribution of BCRs for the NED plan.

Net expected annual benefits estimates for the NED plan range from a low of $3,269,000 to a high of $35,561,000. Expected annual net benefits are $20,344,000.

	400' Channel	500' Channel	600' Channel	700' Channel	800' Channel	900' Channel	1000' Channel
Trans Cost Savings	23,963	23,963	23,963	23,963	23,963	23,963	23,963
Depth Safety	5,281	5,281	5,281	5,281	5,281	5,281	5,281
Width Safety	0	2,060	2,832	3,450	4,017	4,635	4,738
Total Benefits	29,244	31,304	32,076	32,694	33,261	33,879	33,982
Project Costs	87,464	102,902	122,987	143,089	163,206	183,344	203,547
Annual 1st Costs	7,666	9,019	10,780	12,542	14,305	16,069	17,841
Annual O&M Costs	2,353	2,768	3,308	3,849	4,390	4,932	5,475
Total Annual Costs	10,019	11,787	14,088	16,391	18,695	21,001	23,316
Net Benefits	19,225	19,516	17,988	16,303	14,565	12,878	10,655
BCR	2.92	2.66	2.28	1.99	1.7800	1.6100	1.4600
Probability BCR > 1	1.00	1.00	1.00	1.00	0.9988	0.9965	0.9912

Table 21: Economic Summary of Alternative Plans' Most Probable Future Conditions

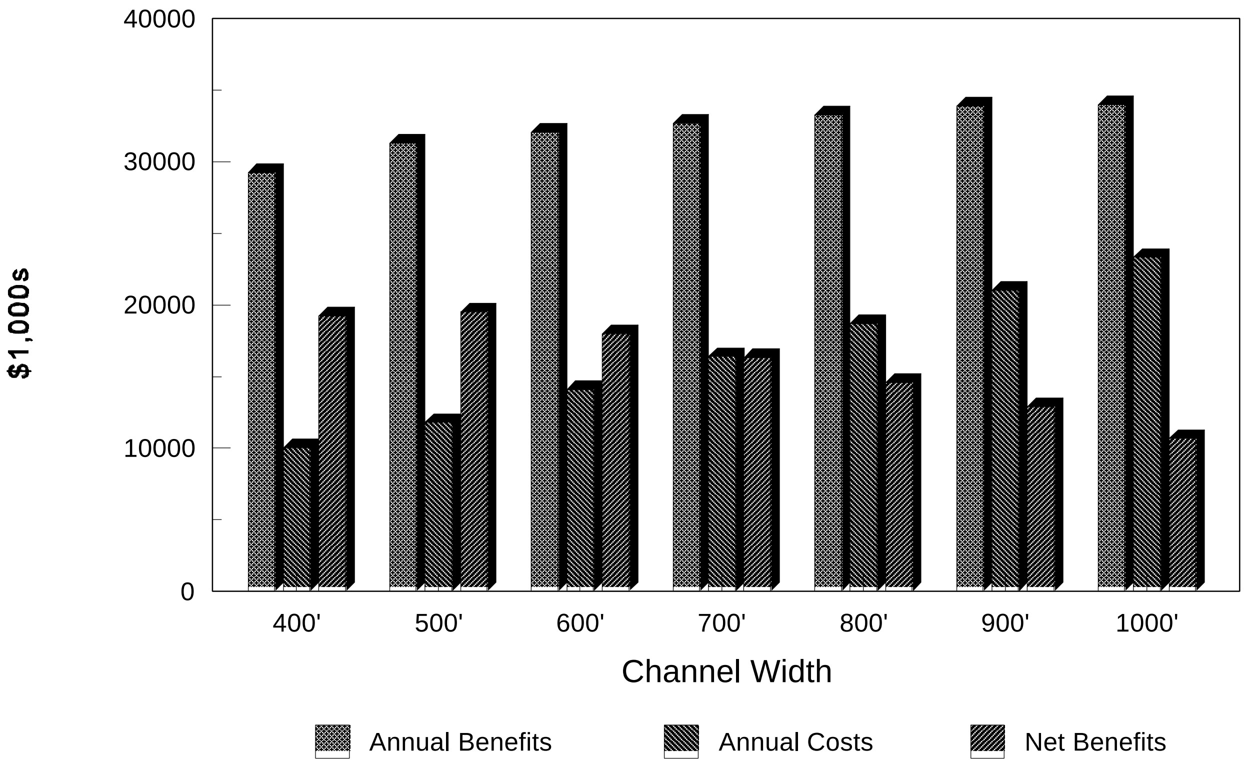


Figure 17: Summary Economics for 55' Projects

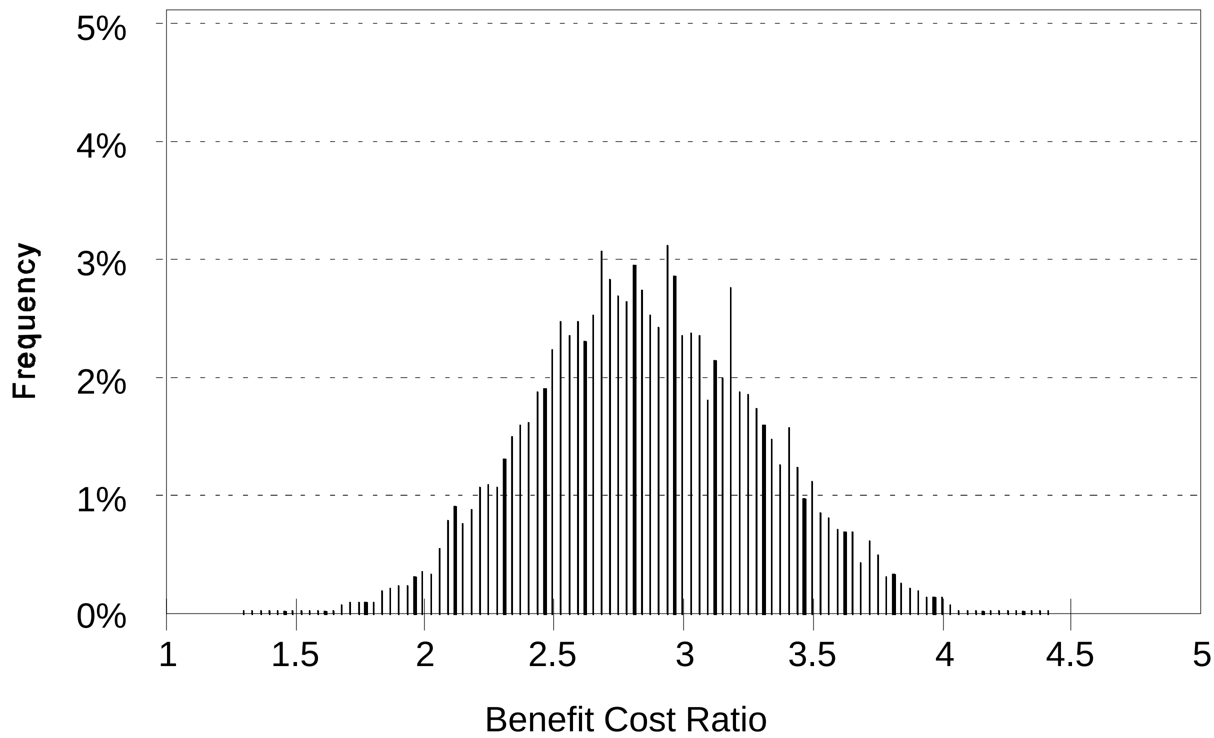


Figure 18(A): BCR Frequency Histogram

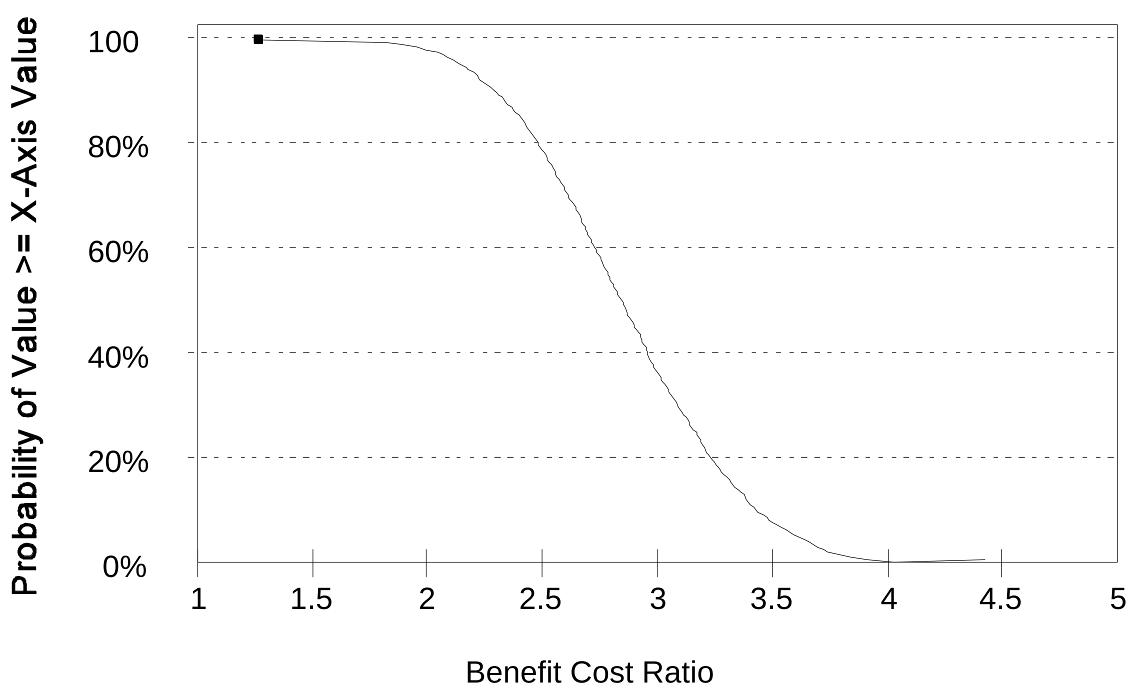


Figure 18(B): BCR Cumulative Frequency

	Mean	Standard Deviation	Minimum	Maximum
Trans Cost Savings	23,963	4,248	8,931	39,426
Depth Safety Ben	5,281	1,897	1,010	12,353
Width Safety Ben	2,102	733	554	4,834
Total Benefits	31,346	4,691	14,789	46,606
Project Costs	87,464	4,015	73,281	101,558
Annual 1st Costs	7,666	352	6,423	8,902
Annual O&M	1,983	146	1,556	2,464
Total Annual Costs	11,002	518	9,276	12,937
Net Benefits	20,344	4,730	3,269	35,561
BCR	2.86	0.45	2.13	3.62

Table 22: Distribution of NED Plan Economic Variables ($1,000's)

Table 22 summarizes the distribution of values for the NED plan. Construction costs exhibit the range described earlier. Annual O&M cost estimates range from $1,556,000 to $2,464,000; total annual costs from $9,276,000 to $12,937,000; and total annual benefits from $14,789,000 to $46,606,000.

The NED plan does not provide the channel width that local interests would prefer. Risk and uncertainty analysis, conducted throughout the planning process, yields information that may be useful in deviating from the NED plan.

First, it has already been noted that under a worst-case risk and delay cost scenario, a 600-foot project yields maximum net benefits. Although the probability of this worst-case scenario is negligible, risk averse decision-makers have the option of assuming worst-case scenarios as the appropriate decision framework.

Second, all projects are economically feasible. Table 21 indicates that there is less than a one percent chance the 1,000-foot wide channel is not economically justified. Only the 900 and 800-foot projects have an effectively, non-zero probability of a BCR less than 1, and each is less than that of the 1,000-foot alternative.[29]

[29] The probabilities presented here differ from those presented earlier, when channel depth alone was considered. Consideration of all formulation issues introduces additional benefit and cost categories. These benefits and costs alter the distribution of the BCR to the values presented here.

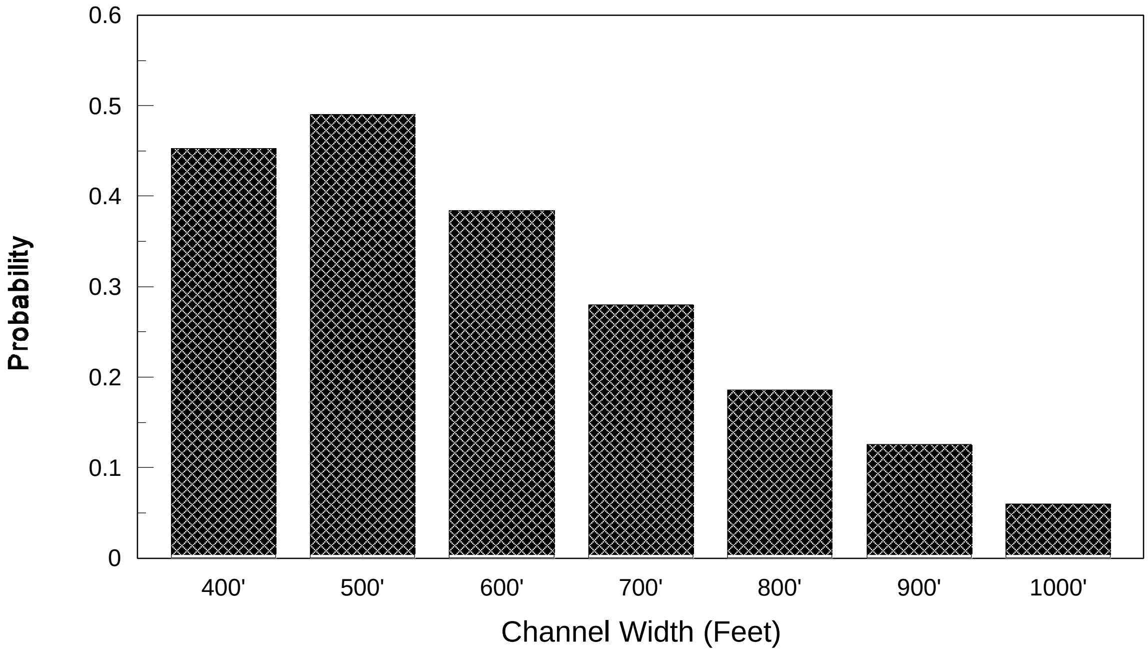


Figure 19: Probability Project Benefits Will Exceed Expected Value of NED Plan Benefits

Third, if the expected net benefits of the NED plan are $20.3, there is some probability that each of the other alternatives will yield benefits of that much, despite their lower expected value. Figure 19 shows the probability of expected annual net benefits being greater than or equal to expected NED benefits of $20.3 million.

As can be seen in Figure 19, there is a 0.49 chance the actual benefits of the NED plan will equal or exceed the expected value.[30] There is a 0.38 chance that benefits will equal or exceed the NED value with a 600-foot wide project. There is still a better than 1-in-4 chance of benefits in this range with an 700-foot channel.

Such arguments ignore the fact that there is a greater probability of benefits in excess of the expected NED amount with the 500-foot channel. This, however, is an irrelevant argument for the decision-makers. Using expected NED benefits as the benchmark, a risk management tradeoff becomes evident.

Decision-makers can choose a wider channel that yields greater safety and enjoys more local support in exchange for a diminished probability of achieving NED-level benefits. Without risk and uncertainty analysis, the tradeoff would simply be that wider channels can be had at a cost to net benefits. The current tradeoff, though similar, has a significant difference. Yes,

[30] Based on the 4,000-iteration simulation results of this analysis. The probabilities presented in this analysis are not analytical values.

expected benefits from wider channels are less. Arguments for or against a non-NED width can still be advanced on this basis. However, analysts are now able to say that choosing a wider channel does not mean foregoing NED-magnitude benefits. There is still a probability of obtaining NED-magnitude benefits; it is simply lessened by wider channels.

The question of the best channel width looks different once net benefits are recognized as a random variable. There is no certainty that the NED plan will yield $20.3 million in benefits. According to the analysis presented here, there is only a 1-in-2 chance that actual benefits will reach this magnitude or greater. Thus, it is not difficult to consider a project where the probability of net benefits in excess of $20.3 million declines to slightly better than 1-in-3.

With a 500-foot wide channel, the present value of risk and delay costs is about $35.1 million. A 600 or 700-foot wide channel would have $26.3 or $19.3 million in risk and delay costs. A 700-foot wide channel would reduce risk and delay costs by about 45 percent over the 500-foot wide channel levels.

The probability of a catastrophic event occurring on any one transit under existing conditions is expected to be about 1-in-2,000,000. This probability is reduced to about 1-in-3,333,333 for a 500-foot wide channel and 1-in-6,060,606 for a 700-foot wide channel.[31] Table 23 provides a comparison of residual probabilities for the various risk and delay events.

With a 700-foot channel, risk and delay events are nearly twice (1.8) as unlikely as they are with the 500-foot channel. The residual risk of a catastrophic event, complete with extensive environmental damage, is roughly one in six million, nearly half the residual risk associated with a 500-foot channel. Though the earlier marginal analysis indicates a 0.027 chance that the

	400' Channel	500' Channel	600' Channel	700' Channel	800' Channel	900' Channel	1000' Channel
Catastrophe	2,000,000	3,333,333	4,444,444	6,060,606	9,090,909	20,000,000	25,000,000
Collision	7,289	12,148	16,197	22,087	33,130	72,886	91,108
Ramming Non-Nav Aid	10,870	18,116	24,155	32,938	49,407	108,696	135,870
Grounding & Other	5,459	9,098	12,130	16,541	24,811	54,585	68,231
Delay	3	5	7	9	14	30	38

S))))))))))
Table values are reciprocals of probabilities, i.e., they are the number of transits expected to yield a single event.

Table 23: Probability of Risk and Delay Events by Channel Width

[31] The existing expected probability of a catastrophe on any one transit is 0.0000005, or 1-in-2,000,000. A 500-foot channel is expected to diminish 40 percent of all catastrophes, thus the chance of a catastrophe is the residual chance (0.6) times the existing chance, or 0.0000003. The probability of a catastrophe per transit with a 700-foot channel is 0.00000017.

incremental channel width is economically justified, there is virtually no chance that the 700-foot wide 55-foot deep channel has a BCR less than 1.

The recommended plan for Star City is to construct the 55-foot deep, 700-foot wide channel. Though this project is not the NED project, it was selected based on the results of risk and uncertainty analyses. Those results are reiterated below.

First, there is a virtual certainty that the project is economically feasible. The minimum BCR estimated was 1.28. Second, there is a 0.28 chance that the recommended plan will have expected NED-level net benefits. Third, the residual risk to navigation, and consequently to the environment, is substantially less, despite the fact that this reduction in risk is not likely to be economically justified. The residual risk of catastrophe is nearly halved by the width increase. Fourth, under a worst-case scenario, a channel width between 600 and 700 feet appears to be optimal.

On balance, the recommended plan makes a greater contribution to planning objectives 1, 3, 4, and 7 than does the NED plan. The recommended plan may not maximize net benefits, but, with expected net expected annual benefits of $17.5 million, it substantially contributes to the second objective of improving economic efficiency.

EPILOGUE

The preceding analysis of a hypothetical case study indicates that the results of risk and uncertainty analyses, far from providing a basis for "killing" projects, can be used constructively in the plan formulation process. The above paragraphs show how decision-makers can use the results of risk and uncertainty assessment as a reasonably argued justification for deviating from the NED plan.